NAVORD REPORT 6969

EVALUATION OF AQUEOUS DISPERSIONS OF TFE-FLOUROCARBON RESINS (TEFLON) APPLIED AS THIN FILMS TO METAL SUBSTRATES

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U.S. NAVAL WEAPONS PLANT

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ABSTRACT: TFE-resin "Teflon" coating systems were prepared on steel and aluminum specimens from proprietary TFE-resin primer and enamel coating material. The resultant 68 systems were evaluated using visual and microscopic examination, film thickness, surface roughness, adhesion, accelerated corrosion (salt spray and high humidity), and wettability tests. The results show the four primers to provide good adhesion and equal corrosion protection, the corrosion protection to be dependent on the total film thickness, the black and white enamels to provide superior corrosion protection, and the gray enamel to provide inferior protection. The rate of heating to TFE-resin sintering temperatures of two aluminum alloys with increasing cross sectional thickness in the uncoated condition, and with one, two, and three coats of TFE-resin was investigated to determine the time required to sinter TFE-resin coatings on various size pieces. Also, the effect of the TFE-resin sintering process on the mechanical properties of two representative aluminum alloys of various hardnesses was determined. The properties of the hardened alloys were effectively reduced to those of the annealed state.

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1. TFE-fluorocarbon resin coatings were applied to steel and aluminum panels. The results of tests on these coated panels are reported. Tests also were performed for rate of heatings and for mechanical property effects of some aluminum alloys in their use as substrate material. This work was authorized by Bureau of Naval Weapons Task Assignment No. 090-708-80001-80047, Serial Nos. 416, 420, 424 of 1 September 1959.

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INTRODUCTION

Previous reports such as NAVWEPS OD 10362[1], NAVWEPS Report 6948[2] and NAVWEPS Report 6949[3], as well as the report of this investigation, deal with thin films of "Teflon" applied to metal substrates. "Teflon" is the registered trade-mark for a family of DuPont fluorocarbon resin products. They are either tetrafluoroethylene resins (TFE-fluorocarbon resins) or fluorinated ethylene propylene resins (FEP-fluorocarbon resins). The "Teflon" used in this and the above reports was the TFE-fluorocarbon resins (TFE-resins) in form of stabilized aqueous dispersions. These aqueous dispersions of small particles of TFE-resins and inorganiz additives are proprietary primers and enamels, (clear and colored) formulated by the Finishes Division of E. I. DuPont de Nemours and Company (Inc.).

As a film, one of the outstanding applications of TFE-resin is as a dry film lubricant; that is, if the film is thin enough to permit the substrate to contribute to the load carrying capacity of the film. For use primarily as a dry film lubricant, the thin TFE-resin film should not exceed 1.0 mil (0.001 inch) in thickness.[4] Considering the above condition, most of the coating systems of this investigation are less than 1.0 mil in thickness. Films thicker than 1.0 mil were also evaluated because of their applicability to conditions other than lubrication. Corrosive environments, antisticking conditions, and extreme temperature conditions are additional situations in which TFE-resin films have excellent utility.

For application of the aqueous dispersions of TFE-resins, the procedures were essentially those used in references 1, 2, and 3. This dispersions were applied to aluminum and steel panels and blocks as thin films. Both the film and substrate material were evaluated from results of quality tests; however, no extensive tests were performed to determine the set of conditions which gave the best films for use in this investigation. All dispersions were sprayed similarly and sintered for periods of time depending on the number of coats of TFE-resins. Because of the variety of dispersions of TFE-resins available, many combinations of TFE-resin films as coating systems were evaluated in this investigation.

This report includes experimental data on uncoated aluminum alloys subjected to heating cycles encountered in the sintering of TFE-resins, see Part 2.

The purpose of this investigation was to obtain data from quality tests

of TFE-resin films on metal substrates so that the following documents could be prepared:

1. A specification for thin films of TFE-resins applied to metal substrates.

2. An ordnance data document for applying thin films of TFE-resins to aluminum alloys.

3. A revision of NAVWEPS OD 10362, Application of Thin Films of TFE-resins to Ferrous Materials.

EXPERIMENTAL PROCEDURE

Aqueous Dispersions of TFE-Resins. Available aqueous dispersions of TFE-resins were obtained from E. I. DuPont de Nemours and Co. (Inc.). The TFE-resins are listed and are designated in the following table:

Table 1 - Aqueous Dispersion of TFE-Resins

Primers		Designation for This Investigation
850-201	Primer for Steel	A
850-202	Primer for Aluminum	B
850-204	Primer (Green) for Steel	C
851-204	One-Coat Enamel	D
Enamels		
851-201	Gray Enamel	1
851-202	White Enamel	2
851-203	Red Enamel	3
851-205	Black Enamel	4
851-206	Blue Enamel	5
851-207	Yellow Enamel	6
851-214	Green Enamel	7
852-201	Clear Finish	8

Application of TFE-Resins to Metal Substrates. The metals used as the subtrates were aluminum and steel in panel form. The aluminum panels were 5.50 inches by 4.25 inches and 5.50 inches by 1.25 inches prepared from 0.064 inch sheet stock, mill finish of aluminum alloy 5056-0. The steel panels, 6.00 inches by 4.00 inches 6 inch by 1.25 inches, were prepared from 16 gauge (0.06-inch thick) cold rolled, satin finish, meeting Federal Specification QQ-S-692, Class A.

The steel panels were sandblasted with No. 145 silica sand at a pressure of 100 psi after having been degreased first in varsol, then in acetone. The aluminum panels were degreased in the same manner, but they were not sandblasted.

Before applying the TFE-resin as thin films, all panels were oxidized at 700°F for 10 to 30 minutes, then air cooled to room temperature. This operation was to remove any gaseous or organic material that might later be trapped between the TFE-resin film and the substrate. The steel panels were oxidized the same day they were sandblasted, or they were stored in a dessicator until oxidizing.

The oxidized panels were sprayed on one side and on the edges with the various TFE-resin primers, aluminum primer on the panels of the aluminum alloy and the other primers on the steel panels. The spray gun was a DeVilbiss TGA type, fitted with a No. E90 nozzle. Adequate oil, dirt, and moisture traps and separators were used. The operation pressure was 30 to 40 psi. The spray gun was held 3 to 8 inches from the panels being sprayed. A film thickness of 0.2 to 0.3 mils was anticipated.

The coated panels were air dried at room temperature for varying lengths of time, usually overnight. To insure complete evaporation of the water from the film (fusing a wet film may cause pinholes or blisters), the panels were placed in a room temperature furnace which was then raised to 180°F. The temperature was maintained for 10 minutes, then increased to 700°F and held for 10 minutes, then increased to 700°F and held for 10 minutes. The furnace was then opened and the fused films were quenched with a water spray.

The enamels were applied, dried, and fused in the same manner as the primers except for each additional coating, 5 minutes was added to the fusing time. This was done because the TFE-resin has low thermal conductivity and absorbs heat as it undergoes the phase change. Panels with thicker films require a longer time to attain the fusing temperature. The films were buffed after each coating with clean canvas cloth to remove the dull finish (dust) of the fused film.

The furnace used in this investigation for the oxidation, drying, and fusing was a large, walk-in, recirculating hot-air type with good exhaust. The accuracy of temperature control was within 5°F.

Coating System. The systems with one coat of primer plus a single coat of enamel were prepared so that each primer with each enamel as a topcoat was evaluated. The systems of steel primer (A) plus multiple coats of each enamel were prepared in order to evaluate the enamels as the thickness of the coating system increased. It was unnecessary to use more than one primer for this purpose. The systems of one coat of steel primer (A) plus one coat of each enamel plus one coat of clear finish, were evaluated because these are systems which would logically be used where thick films are required. The system of two coats of one-coat enamel, was evaluated because it had been used often in the past. The one-coat enamel was also evaluated as a primer because it is used so extensively, and the question of possibility of its use as a primer had been raised. A total of 68 coating systems were evaluated.

Tables 2 through 7 list the various combinations of the TFE-resins that were prepared for evaluation in this investigation, show how they were designated, and show the number group of the panels to which they were applied.

TABLE 2 - TFE - RESIN COATING SYSTEM
(STEEL PRIMER A: TOPCOAT - ONE COAT OF THE ENAMELS)

Coating System		Designation#	Panel Numbers	
			L-Panels*	S-Panels**
850-201 851-201	Primer for Steel Gray Enamel	A1	1-12	685-687
850-201 851-202	Primer for Steel White Enamel	A2	13-24	688-690
850-201 851-203	Primer for Steel Red Enamel	A3	25-36	691-693
850-201 851-205	Primer for Steel Black Enamel	A4	37-48	694-696
850-201 851-206	Primer for Steel Blue Enamel	A5	49-60	697-699
850-201 851-207	Primer for Steel Yellow Enamel	A6	61-72	700-702
850-201 851-214	Primer for Steel Green Enamel	A7	73-84	703-705
850-201 852-201	Primer for Steel Clear Finish	A8	85-96	706-708
850-201	Primer for Steel	A	838-841	

#The alphabet of the coating system designation represents the primer used.
The numberal represents the enamel used. Repetition of either alphabet or numberal indicates an additional coating to correspond to the repetition; e.g., A111 is a coating system of one coat of primer (A) and three coats of gray enamel.

*L-Panels: 5.50-inch by 4.25-inch aluminum panels and 6.00-inch by 4.00-inch steel panels used for visual and microscopic examination, corrosion, surface roughness or general testing.

**S-Panels: 5.50-inch by 1.25-inch aluminum panels and 6.00-inch by 1.25-inch steel panels used for adhesion testing.

TABLE 3 - TFE - RESIN COATING SYSTEM
(ALUMINUM PRIMER B; TOPCOAT - ONE COAT OF THE ENAMELS)

Coating System		Designation	Panel Numbers	
			L-Panels	S-Panels
850-202 851-201	Primer for Aluminum Gray Enamel	B1	846-857	942-944
850-202 851-202	Primer for Aluminum White Enamel	B2	858-869	945-947
850-202 851-203	Primer for Aluminum Red Enamel	B3	870-881	948-950
850-202 851-205	Primer for Aluminum Black Enamel	B4	882-893	951-953
850-202 851-206	Primer for Aluminum Blue Enamel	B5	894-905	954-956
850-202 851-207	Primer for Aluminum Yellow Enamel	B6	906-917	957-959
850-202 851-214	Primer for Aluminum Green Enamel	B7	918-929	960-962
850-202 852-201	Primer for Aluminum Clear Finish	B8	930-941	963-965
850-202	Primer for Aluminum	B	966-969	

TABLE 4 - TFE-RESIN COATING SYSTEM
(STEEL PRIMER C; TOPCOAT - ONE COAT OF THE ENAMELS)

Coating System		Designation	Panel Numbers	
			L-Panels	S-Panels
850-204 851-201	Primer (Green) for Steel Gray Enamel	C1	97-108	709-711
850-204 851-202	Primer (Green) for Steel White Enamel	C2	109-120	712-714
850-204 851-203	Primer (Green) for Steel Red Enamel	C3	121-132	715-717
850-204 851-205	Primer (Green) for Steel Black Enamel	C4	133-144	718-720
850-204 851-206	Primer (Green) for Steel Blue Enamel	C5	145-156	721-723
850-204 851-207	Primer (Green) for Steel Yellow Enamel	C6	157-168	724-726
850-204 851-214	Primer (Green) for Steel Green Enamel	C7	169-180	727-729
850-204 852-201	Primer (Green) for Steel Clear Finish	C8	181-192	730-732
850-204	Primer (Green) for Steel	C	842-845	

TABLE 5 - TFE-RESIN COATING SYSTEM
(PRIMER - ONE COAT ENAMEL; TOPCOAT - ONE COAT OF ENAMEL)

Coating System	Designation	Panel Numbers	
		L-Panels	S-Panels
851-204 One-Coat Enamel 851-201 Gray Enamel	D1	193-204	733-735
851-204 One-Coat Enamel 851-202 White Enamel	D2	205-216	736-738
851-204 One-Coat Enamel 851-203 Red Enamel	D3	217-228	739-741
851-204 One-Coat Enamel 851-205 Black Enamel	D4	229-240	742-744
851-204 One-Coat Enamel 851-206 Blue Enamel	D5	241-252	745-747
851-204 One-Coat Enamel 851-207 Yellow Enamel	D6	253-264	748-750
851-204 One-Coat Enamel 851-214 Green Enamel	D7	265-276	751-753
851-204 One-Coat Enamel 852-201 Clear Finish	D8	277-288	754-756
851-204 One-Coat Enamel 851-204 One-Coat Enamel	DD	289-300	757-759
851-204 One-Coat Enamel	D	301-312	760-762

Table 6 - TFE-Resin Coating System (Steel Primer A: Topcoat - Two, Three, and Four Coats of the Enamels)

	Designation of Multiple Top Coated L Panels					
Coating System	Three Coats	Panel No.	Four Coats	Panel No.	Five Coats	Panel No.
850-201 Primer for Steel 851-201 Gray Enamel	A11	397-408	A111	409-420	A1111	421-432
850-201 Primer for Steel 851-202 White Enamel	A22	433-444	A222	445-456	A2222	457-468
850-201 Primer for Steel 851-203 Red Enamel	A33	469-480	A333	481-492	A3333	493-504
850-201 Primer for Steel 851-205 Black Enamel	A44	505-416	A444	517-528	A4444	529-540
850-201 Primer for Steel 851-206 Blue Enamel	A55	541-552	A555	553-564	A5555	565-576
850-201 Primer for Steel 851-207 Yellow Enamel	A66	577-589	A666	589-600	A6666	601-612
850-201 Primer for Steel 851-214 Green Enamel	A77	613-624	A777	625-636	A7777	637-648
850-201 Primer for Steel 852-201 Clear Finish	A88	649-660	A888	661-672	A8888	673-684

Table 7 - TFE-Resin Coating System (Steel Primer A; Topcoat - One Coat of Enamel and One Coat of The Clear Finish)

Coating System	Designation of Multiple Top-Coated L-Panels Three Coats	Panel No.
850-201 Primer for Steel 851-201 Gray Enamel 852-201 Clear Finish	A18	313-324
850-201 Primer for Steel 851-202 White Enamel 852-201 Clear Finish	A28	325-336
850-201 Primer for Steel 851-203 Red Enamel 852-201 Clear Finish	A38	337-348
850-201 Primer for Steel 851-205 Black Enamel 852-201 Clear Finish	A48	349-360
850-201 Primer for Steel 851-206 Blue Enamel 852-201 Clear Finish	A58	361-372
850-201 Primer for Steel 851-207 Yellow Enamel 852-201 Clear Finish	A68	373-384
850-201 Primer for Steel 851-214 Green Enamel 852-201 Clear Finish	A78	385-396

Test Procedures. To evaluate the TFE-resin coating systems on the steel and aluminum panels, systematic testing of various properties contributing to the quality of the coating was performed. At the same time, the tests were evaluated as quality control procedures. The tests conducted in this investigation were as follows:

Visual and Microscopic Examination. Extensive unaided eye and microscopic examinations were made of the TFE-resin films before and after many of the tests. Film color, local discoloration, continuity, and gross defects were observed with the unaided eye. Using a stereoscopic microscope with an outside light source, a survey examination was made at 10.5X, 30X, 60X, and 75X magnification. For more detailed examination, a microscope with a vertical light source capable of 80X, 100X, 160X, 200X, 400X and 800X magnification was used. This microscope was also equipped with a 35mm camera attachment which was used to make photographic studies.

Film Thickness. Sintered TFE-resin film thickness was measured on each of the L-panels of all of the coating systems. Measurement of the film thickness on the steel panels was made with an Aminco-Brenner Magne-Gage; measurement on the aluminum panels was made with an Aminco Filmeter. The accuracy of each instrument is approximately ±10 percent. Readings were taken at four points on each panel and were averaged to give the panel film thickness. It was desired during the preparation of the panels to apply 0.2#-#0.3 mils per coating.

Surface Roughness. The surface roughness of the TFE-resin film on four panels of each coating system was determined with a Brush Surfindicator, Model BL-110 using a Motor Drive, Model BL-114. This instrument records, in microinches, the average height about an imaginary mean line parallel to the general direction of the profile of the surface, so that the sums of the areas contained between it and those parts of profile which lie on either side of it, are equal. The surface of the uncoated side of the panels was also measured in order to obtain any change in surface roughness due to the film.

Adhesion. Each of the coating systems, consisting of a primer and one coat of enamel, had been applied to the S-panels and was qualitatively tested for adhesion using a Shore Durometer, Type A, and using a bend test.

The Shore Durometer contains a spring-loaded, flatten, conical probe which is retracted when pressed downward on a flat surface. The vertical force exerted is approximately 2350 psi. When the durometer is slid in the direction of its longest dimension across a panel, unfused or non-adherent TFE-resin films are visibly ploughed or detached; satisfactory films are not damaged.

The bend test consists of bending the panel, with one end held securely in a vise, back and forth until the metal substrate fractures. If the TFE-resin film blisters or becomes detached from the substrate, in any way, before the metal fractures, it is considered to have poor adhesion.

An indication of the adhesion of the films was also accomplished by rubbing a rounded steel probe across the film surface while observing the effect on the film at 30X magnification.

<u>Accelerated Corrosion</u>. The resistance to corrosion of the various TFE-resin coating systems was evaluated using two accelerated corrosion tests: (1) Three panels of each coating system, were tested according to Method 811 of Fed. Test Method Std. No. 151 using a 20 percent salt solution. The panels remained in the test cabinet for a maximum of 336 hours, or were removed when a general breakdown of the film became evident. Examination of the panels was made after 3, 8, 24, 32, 48, 72, 100, 144, 192, 228, 265, and 336 hours of exposure. (2) Three panels of most of the coating systems were tested at $120^{\circ} \pm 2^{\circ}F$ and 100 percent relative humidity according to Specification JAN-H-792. Examination was made at the same time intervals as for the salt spray test. Panel exposure was also continued for 336 hours or until general breakdown became evident.

In each test, time to initial corrosion, total exposure time, and final condition were recorded.

The humidity test also serves as a test of the adhesion of the individual films to each other. If poor adhesion is present, blisters will be formed at the interfaces of film layers.

<u>Wettability</u>. NRL Memorandum Report 777[5] states that wettability of TFE-resin (Teflon) coatings is "indicative of the nature and closeness of packing of the atoms or organic radicals comprising the outermost surface of the coating. Large contact angles with water are indicative of high water repellency and hence decreased corrosiveness by rain and lower iced adhesion. Large contact angles with methylene iodide and hexadecane would indicate low hydrogen and high fluorine content, low adhesion of liquids including oils, and low adhesion of solids including airborne debris".

This NRL report also stated that the wetting characteristics of water, methylene iodide, and n-hexadecane as obtained by simple contact angle measurements may be used as a method of quality control of TFE-resin coated items. For example, contact angles on TFE-resin (850-204) coatings for sessile drops of the three above liquids were 122°, 90°, and 46° respectively.

To extend this work, this investigation included all the available primers and enamels as coatings, then contact angles were determined. Laboratory distilled water, and methylene iodide and n-hexadecane purchased from the Fisher Scientific Co. were used as the liquids. Drops of these

liquids were put on the TFE-resin coated panels which had been cleaned with a detergent, rinsed with distilled water, and dried at 220°F for 2 hours. The liquid was applied to the panels as follows: One drop was applied and measured, then another drop was added to the first, and a second measurement was made. In the case of methylene iodide, extreme care was taken in putting the drops on the panel. The drops were distorted or fattened if allowed to fall on the panel.

Measurement of the contact angles of the drops of the solutions were made with an optical comparator where the profile of the drops were shown on a protractor screen in a 31.25X magnification. The profile of the drops in reduced size appeared approximately as pictured in figure No. 1.

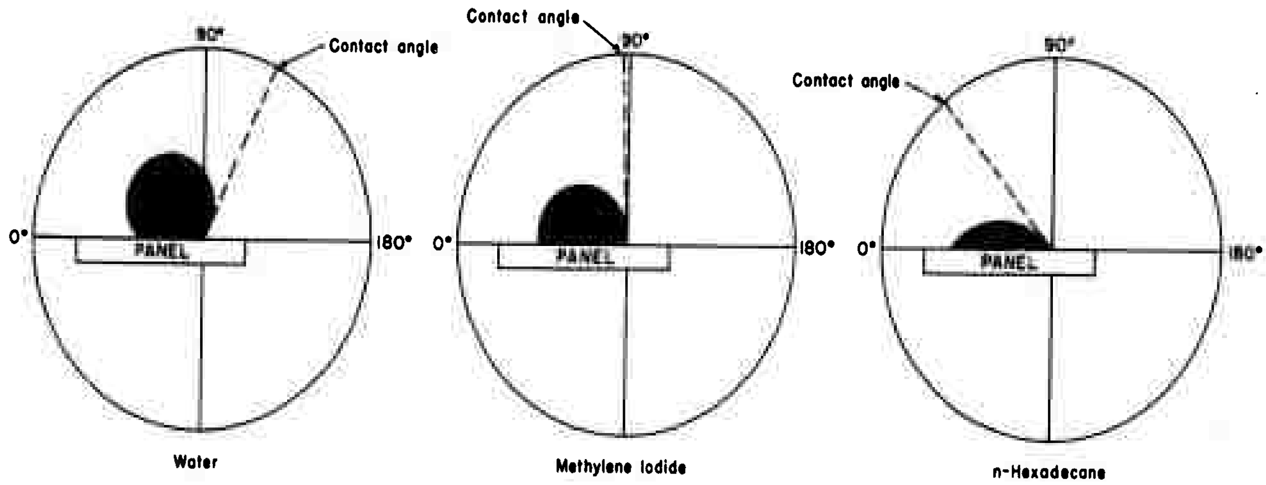

Figure 1 - Profile of Sessile Drops Viewed on Protractor Screen

By rotating the circular disk, graduated in half-degree divisions, the angle of contact of the drops of liquid on the TFE-resin coated panels was determined.

By correlating the contact angles of the three liquids to frictional measurements, the minimum acceptable contact angles for water, methylene iodide, and n-hexadecane on TFE-resin coated surfaces are 95°, 81° and 35° respectively.[5]

RESULTS AND DISCUSSION

Visual and Microscopic Examination. Unaided eye examination shows all of the TFE-resin coating systems to be continuous films, free from gross defects such as mudcracks, pinholes or craters, sags, wrinkles, and blisters. The only imperfections noted were particles of TFE-resin up to 1/32 inch diameter which formed raised spots on the film surface, or protruded from it as short strings. These heavy spots of TFE-resin were the result of the spraying technique and could easily be removed with light sanding using #3/0 emery paper.

The hue of the different TFE-resin enamels by which they are distinguished from each other is good. However, one coat of Clear Finish over the various primers shows colors similar to a single coat of the gray enamel on the respective primers; as the topcoats become thicker the gray enamel appears gray while the Clear Finish shows a bluish tint. The other enamels do show some variations in tinting when applied to the various primers, and the color or hue becomes more intense as the enamel thickness is increased. The enamel hue is distinct, and the enamels are easily distinguished from each other, except for the gray enamel and the Clear Finish.

The TFE-resin coating material used to prepare the specimens for this investigation were from the same lot and in many cases from the same bottle. Although color matching was good here, it cannot be assumed that the same will be true when using coating material prepared at different times.

A topcoat of Clear Finish over the enamels appears to add gray to their color and, in the case of the white enamel, caused mottling. The A18 coating system was the only indication of non-compatibility and it could be detected by none of the other quality tests.

In addition to the above attributes, the TFE-resin films could all be considered lusterless, even after buffing with canvas cloth.

At magnifications up to 75X the enamel films were seen to be made up of small globules of TFE-resin which have fused together at their contacting surfaces. Since there is little or no flow of the resin at the sintering temperature, the globules do not flatten, and nodules remain in the surface of the film giving the appearance of hammered metal work. As the enamel film thickness is increased, the gray, white, yellow, and green enamels tend to lose this appearance; and a smoother, continuous film is formed. The red, black and blue enamels, and the Clear Finish retain the nodular appearance. No nodules are evident with the primers, which form smooth

continuous coatings. With primer films less than 0.2 mil thick, many of the peaks (due to the sandblast) which make up the surface of the substrate metal are not completely covered.

Where the enamel gives good color contrast with the primer in the two-coat systems up to an enamel film thickness of approximately 0.3 mil, it is evident that the enamel does not form a continuous film of the primer.

The thinner enamel films have many voids, with up to 20 percent of the area showing the primer. As the thickness of the enamel is increased, the voids are filled in until only pinholes or small craters remain. This last condition is considered a continuous film which is pinholed. A second coat of enamel fills in the voids and covers the pinholes, but the second coat itself contains pinholes. Successive coats seal the pinholes or craters of the previous coating but produce pinholes of their own. The final result is a continuous film with pinholes from layer to layer of TFE-resin. These pinholes are visible at 30X or greater magnification.

When the One-Coat Enamel is used as a topcoat (systems DD and AD) it is seen to be mudcracked and pinholed at 30X magnification. The pinholes are joined by the mudcracks and both appear to be only in the topcoat. This is the only topcoat which was found to be mudcracked. The other topcoats (enamels or clear finish) all contain varying numbers of pinholes or craters which appear to exist only through the topmost coating.

At 400X magnification aluminum and steel (A) primer films were found to have a crystalline appearance with dark lines separating irregularly shaped areas which are repetitive. The dark lines are not cracks. This condition could not be found with the One-Coat Enamel and the green steel primer (C) up to 800X magnification.

All of the primers have a grainy appearance at 400X magnification. They seem to be made up of very small particles separated by a semi-transparent medium. With the aluminum and steel (A) primers the particles are gray, with the green steel (C) primer and the One-Coat Enamel they are light green. The grainy appearance was also noted with some of the topcoats when observed at 400X magnification; hundreds of particles make up a single nodule of the TFE-resin film. The red, yellow, and green enamels have particles which are pigmented the same color as the enamel. The white and black enamels and the Clear Finish have white particles with the medium separating them being the color of the enamel. The blue and gray enamels and the Clear Finish in systems A8, A88, and as a topcoat on the enamels contain very few particles. The appearance is not grainy, but waxy. The Clear Finish in this condition is transparent and the primer and enamel can be seen through it.

It was thought that these grains were TFE-resin particles which had not been completely fused or sintered. After resintering a series of coating systems containing the various enamels and Clear Finish at 760°F for 30 minutes and again at 800°F for 30 minutes, no change was found in the grainy appearance. The particles are, therefore, not the result of incomplete fusion.

Film Thickness. The results of the film thickness measurements are summarized in table 3. For each coating system the maximum value is the fused film thickness of the panel with the thickest film; the minimum value is the film thickness of the panel with the thinnest film; and the average value is the numerical average of the film thickness of at least 12 panels. All the values are in mils (0.001 inch).

It was expected that film thicknesses for the coating systems would have the following ranges:

Coating System	Thickness (mils)
Primer coat	0.2-0.3
Primer coat plus one coat of enamel	0.4-0.6
Primer coat plus two coats of enamel	0.6-0.9
Primer coat plus three coats of enamel	0.8-1.2
Primer coat plus four coats of enamel	1.0-1.5

When the expected thickness values are compared with the actual values of table 8 the average values for film thicknesses for most of the coating systems are within the limits; however, variation of the film thickness for a particular coating was more than expected. To have a better picture of the film buildup as additional coatings are applied, table 9 was compiled. Table 4 contains the average film thickness, in mils, for the individual coatings. It was obtained by subtracting the average film thickness values of the system containing one less coating. For example, to obtain the thickness of the gray enamel on steel primer, the average steel primer thickness was subtracted from the average Al coating system total film thickness; to obtain the thickness of the fourth coat of gray enamel on steel primer, the average film thickness of the Alll coating system was subtracted from the average film thickness of the Allll coating system.

Table 8 - Total Film Thickness of TFE-Resin Coating Systems (in mils)

Coating System	Max.	Min.	Ave.	Coating System	Max.	Min.	Ave.	Coating System	Max.	Min.	Ave.	Coating System	Max.	Min.	Ave.
A1	0.72	0.43	0.56	A2	0.87	0.48	0.68	A3	0.61	0.39	0.52	A4	0.71	0.52	0.63
A11	0.94	0.60	0.71	A22	0.85	0.51	0.71	A33	0.99	0.72	0.87	A44	1.10	0.82	0.93
A111	1.16	0.87	0.98	A222	1.52	1.15	1.24	A333	1.32	1.09	1.21	A444	1.30	0.98	1.13
A1111	1.37	1.09	1.23	A2222	1.84	1.46	1.60	A3333	1.69	1.13	1.44	A4444	1.46	1.23	1.36
A18	1.76	1.31	1.47	A28	1.76	0.98	1.35	A38	1.38	0.92	1.17	A48	1.35	0.99	1.14
A5	0.71	0.52	0.62	A6	1.31	0.49	0.77	A7	0.45	0.28	0.36	A8	0.98	0.66	0.79
A55	0.94	0.70	0.80	A66	1.35	0.65	0.91	A77	0.68	0.49	0.58	A88	0.88	0.72	0.81
A555	1.32	0.98	1.06	A666	1.46	1.13	1.24	A777	1.13	0.90	0.96	A888	1.32	1.09	1.24
A5555	1.41	0.99	1.12	A6666	1.86	1.56	1.66	A7777	1.46	1.13	1.31	A8888	1.77	1.37	1.60
A58	0.94	0.79	0.84	A68	1.38	0.86	1.03	A78	0.74	0.57	0.66				
B1	0.85	0.58	0.73	C1	0.42	0.31	0.37	D1	0.46	0.33	0.39	A	0.31	0.20	0.25
B2	0.81	0.59	0.74	C2	0.52	0.36	0.43	D2	0.44	0.34	0.39	A *	0.19	0.13	0.15
B3	0.68	0.56	0.62	C3	0.35	0.19	0.27	D3	0.41	0.29	0.33	B	0.42	0.22	0.33
B4	0.92	0.71	0.85	C4	0.49	0.32	0.38	D4	0.66	0.51	0.58	C	0.13	0.11	0.12
B5	0.94	0.76	0.87	C5	0.53	0.41	0.45	D5	0.56	0.34	0.44	D	0.25	0.14	0.17
B6	0.92	0.62	0.75	C6	0.46	0.37	0.42	D6	0.50	0.34	0.42	DD	0.41	0.30	0.36
B7	0.84	0.56	0.71	C7	0.49	0.36	0.41	D7	0.52	0.37	0.46				
B8	1.27	1.09	1.19	C8	0.87	0.49	0.65	D8	0.98	0.58	0.76				

* Primer thickness for A66, A666, A6666, A77, A777, A7777, A88, A888, and A8888.

Table 9 - Thickness of Individual Coatings (in mils)

Enamel X	Coating System X = Enamel								Average Film Thickness per coat
	AX	BX	CX	DX	AXX	AXXX	AXXXX	AX8*	
1	0.31	0.40	0.25	0.22	0.15	0.27	0.25	0.91	0.26
2	0.43	0.41	0.31	0.22	0.03	0.53	0.36	0.67	0.33
3	0.27	0.29	0.15	0.16	0.35	0.34	0.23	0.65	0.26
4	0.38	0.52	0.26	0.41	0.30	0.20	0.23	0.51	0.33
5	0.37	0.54	0.33	0.27	0.18	0.26	0.06	0.22	0.29
6	0.52	0.42	0.30	0.25	0.24#	0.33	0.42	0.26	0.36
7	0.11	0.38	0.29	0.29	0.32#	0.38	0.35	0.30	0.30
8	0.54	0.86	0.53	0.59	0.12#	0.43	0.36		0.50

#0.10 added for primer thickness for A66, A77, and A88.

*Not used in average film thickness per coat.

Surface Roughness. The results of the surface roughness determinations are tabulated in table 10. The surface roughness value is the average for the films on the four panels measured in each coating system. The change in surface roughness was obtained by subtracting from the film surface roughness the average surface roughness of the uncoated side of the panels. Two hundred and seventy seven steel panels gave a value of 59 microinches, and 36 aluminum (unsandblasted) panels averaged 10 microinches. Included in the table is the average total film thickness of the films on which the surface roughness had been determined.

As the film thickness increases, tnere is a general tendency for the surface roughness to increase. This is seen in table 10, rows I and II, column 2. The change in surface roughness of the TFE-Resin coating from the original steel panel surface roughness is shown in column 3. Data in row III shows TFE-Resin surface roughnesses of other coating systems.

The topcoats applied to the unsandblasted aluminum panels have substantially the same surface roughness as topcoats applied to the sandblasted steel panels (the change in surface roughness is much greater on the aluminum panels), indicating that for equivalent film thickness the same surface roughness will result regardless of the surface roughness of the substrate. There are, of course, limits to this: previous investigations[2] have shown that TFE-resin films applied to substrates with surface roughness greater than 150 microinches would produce a film with lower surface roughness.

A maximum surface roughness of 90 micoinches has been previously required for the "Teflon" TFE-resin films which are to have dry lubrication or anti-sticking applications.[6] Of the coating systems with less than 1.0 mil film thickness prepared for this investigation, some exceeded this limit, although the majority did not. During the preparation of the films, no attempt was made to control the surface roughness. If the surface roughness had been controlled, the maximum limit of 90 microinches could have been met. For films of greater thickness than 1.0 mil this surface roughness maximum is not needed although it can easily be obtained by sanding lightly or buffing.

The resin films were examined microscopically after measuring the surface roughness. The diamond stylus of the surfindicator exerts a pressure of approximately 3000 psi on the film resulting in a slight indentation, the width of the stylus. This trace line, however, has no adverse effects on the film, for the panels later corrosion tested showed no corrosion at this line.

Table 10 - Surface Roughness of TFE-Resin Films

	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
I	A	49	-10	0.14	A	49	-10	0.14	A	49	-10	0.14	A	49	-10	0.14
	A1	72	13	0.57	A2	65	6	0.60	A3	77	18	0.56	A4	65	6	0.59
	A11	82	23	0.73	A22	73	14	0.73	A33	134	75	0.92	A44	114	55	0.93
	A111	96	37	1.02	A222	56	-3	1.31	A333	119	-60	1.18	A444	121	62	1.06
	A1111	69	10	1.20	A2222	93	34	1.57	A3333	148	89	1.50	A4444	144	85	1.34
II	A	49	-10	0.14	A	49	-10	0.14	A	49	-10	0.14	A	49	-10	0.14
	A5	66	7	0.62	A6	101	61	0.70	A7	51	-8	0.38	A8	86	27	0.84
	A55	69	10	0.88	A66	80	21	1.01	A77	63	4	0.55	A88	73	14	0.83
	A555	81	22	1.04	A666	99	40	1.19	A777	86	27	0.98	A888	84	25	1.25
	A5555	83	24	1.11	A6666	111	52	1.70	A7777	103	44	1.34	A8888	106	47	1.61
III	A	49			B	41	31	0.34	C	47	-12	0.12	D	37	-22	0.15
	A18	94	35	1.46	B1	73	63	0.75	C1	75	16	0.39	D1	67	8	0.38
	A28	75	16	1.36	B2	48	38	0.78	C2	65	6	0.47	D2	47	-12	0.39
	A38	135	76	1.08	B3	69	59	0.62	C3	66	7	0.30	D3	63	4	0.33
	A48	120	61	1.07	B4	73	63	0.87	C4	74	15	0.39	D4	61	2	0.57
	A58	69	10	0.85	B5	78	68	0.87	C5	73	14	0.47	D5	66	7	0.46
	A68	91	32	1.12	B6	66	56	0.78	C6	61	2	0.41	D6	56	-3	0.44
	A78	69	10	0.71	B7	56	46	0.68	C7	67	8	0.45	D7	45	-14	0.45
					B8	74	64	1.20	C8	111	52	0.66	D8	68	9	0.70
													DD	68	9	0.34

Key:
1 - Coating System
2 - Surface Roughness (Ave. microinches)
3 - Change in Surface Roughness (Ave. Microinches)
- Panel surface roughness originally averaged 59 microinches
4 - Total film Thickness (mils)

Adhesion. The test for adhesion using the Shore Durometer ploughed or detached none of the coating systems prepared in this investigation, indicating that all have adequate adhesion. This test was found to be invalid for extremely thin coatings (0.25 mil and less) on sandblasted surfaces because peaks of the substrate metal are exposed, or so nearly exposed and the probe rides on these peaks.

The bend test also indicated that all of the systems have adequate adhesion. It was, however, noted that the adhesion of the TFE-resins to the unsandblasted aluminum panel was inferior to that of the TFE-resins to sandblasted steel panels, as might be expected. The films on the aluminum panels could be peeled back from the fracture to the area that had not been deformed during the bend test. This could not be done with the films applied to the sandblasted steel panels; but could be with unsandblasted steel panels coated with steel primer (A), indicating that it was entirely the surface conditions which caused the difference in adhesion. From the results of the Shore Durometer test, no variation in adhesion of the TFE-resin films on the sandblasted and the unsandblasted substrates could be detected.

Rubbing the TFE-resin films with a rounded steel probe while observing the effects at 30X magnification, produced the results tabulated in table 11. This test does not indicate the degree of adhesion of the coating systems to the substrate, but it does indicate the degree of adhesion of the individual coatings to each other, especially the adhesion of the top coat(s) to the primer. From the table it can be seen that the adhesion of the individual enamels to each other is better than the adhesion of the enamels to the primers, and the adhesion of the enamels to the steel primer (A) appears to be decreased by the application of additional costs of enamel. The results also indicate that the adhesion of the gray enamel to primers is not quite as good as the other enamels and the Clear Finish.

This test has a tendency to be subjective and, although these test results can be accepted as valid, they should not be used as a general test for adhesion.

Table 11 - Relative Adhesion of the Various TFE-Resin Primers and Enamels

Coating System	Result	Coating System	Result	Coating System	Result	Coating System	Result
A1	B	A11	C	A111	CO	A1111	O
A2	A	A22	C	A222	O	A2222	C
A3	A	A33	C	A333	CX	A3333	COX
A4	A	A44	C	A444	C	A4444	C
A5	A	A55	CO	A555	C	A5555	C
A6	A	A66	C	A666	C	A6666	C
A7	A	A77	CO	A777	C	A7777	C
A8	A	A88	CX	A888	C	A8888	C
A18	XA	B1	AO	C1	C	D1	C
A28	XC	B2	A	C2	A	D2	A
A38	O	B3	A	C3	A	D3	A
A48	C	B4	AO	C4	B	D4	O
A58	C	B5	A	C5	B	D5	A
A68	C	B6	A	C6	B	D6	A
A78	C	B7	A	C7	A	D7	A
		B8	A	C8	B	D8	B
						DD	A

Key:

A - Topcoat and primer removed together as one film.

B - Topcoat and primer removed together but some primer remains.

C - Topcoat(s) removed from primer.

X - Topcoat removed from enamel under it.

O - Not definite.

Accelerated Corrosion Salt Spray. The results of the salt spray test are tabulated in Tables 12 through 18. The first column gives the coating system; the second column, the number of the panel tested; the third column, the average film thickness of the panel tested; and the fourth column, the number of hours exposure when corrosion was first observed, followed by a notation of the type of initial corrosion with the following meanings:

G - General spotting

F - More than 25 spots of corrosion

S - Less than 25 spots of corrosion with the exact number superscribed

OK - No corrosion observed during test

The fifth column gives the total hours of exposure and the sixth column a rating of the final condition according to the following table:

0 - No corrosion

1 - 1-5 spots of corrosion

2 - 6-30 spots of corrosion

3 - 31-100 spots of corrosion

4 - More than 100 spots of corrosion

5 - General spotting but not over the entire panel

6 - Complete breakdown of film

B - Blister(s)

R - Runs of corrosion products

The final rating or evaluation was based on unaided eye and 10X magnification observations, although examination up to 60X was made of the exposed panels. Those panels exposed 264 or 267 hours are not to be considered to have reached the point of complete breakdown. The salt-spray tanks broke down at this time and the tests, which should have been continuous, had to be discontinued.

In almost all instances the thicker TFE-resin films provided better protection than the thinner films regardless of the coating system. The panels coated with films less than 0.8-mil thick generally had considerable corrosion after 24 hours exposure. If a film was going to provide good protection, it was usually indicated after this length of time. In only one case, aside from the gray enamel coatings, did any of the coating systems with a total thickness of 0.9 mil or more have more than 12 spots of corrosion after 32 hours exposure, and none had runs of corrosion products.

To obtain a better picture of the corrosion protection provided by the TFE-resin coating systems they were rating or ranked as systems according to the relative protection they provide. In table 19 the enamels (including the Clear Finish) are rated. In this table systems with different primers are not compared, only those with the same primer. Systems with the same rank are considered to provide equal protection. The thickness value is the average film thickness on the three panels salt-spray tested. From this table, the enamels can be divided into three groups; A#-#good protection: black, white, and yellow; B#-#satisfactory protection: blue, green, and Clear Finish; and C#-#poor protection: gray and red.

In table 20 systems containing the same enamel are rated, systems containing different enamels should not be compared. It is seen that as the total film thickness increases, the salt-spray protection also increases; that the Clear Finish as a topcoat on enamels provides protection approximately equal to an equivalent thickness of the enamel; and that the protection provided by primers A, C, and D is effectively equal. Coating systems containing aluminum primer (B) cannot be compared with systems containing the other primers, because aluminum is subject to a different type corrosion than the steel. Uncoated areas of the aluminum will not necessarily corrode sufficiently to become visible; scratches in the film sometimes showed no corrosion throughout the entire exposure period.

In table 21 the enamels are ranked as to their relative corrosion protection. This rating was based on the evaluation of all the systems containing each enamel including the multiple coating. The black enamel provided the best protection, followed by the Clear Finish, and then the white enamel. The gray enamel provided the least protection, then the red enamel, with the blue, yellow, and green enamel somewhat better and equal.

Table 12 - Salt-Spray Test Results
(Coatings A1 to A1111 and A18, A2 to A2222 and A28)

Coating System	Panel Number	Total Film Thickness (Mils)	Hours to Initial Corrosion	Total Hours Tested	Final Condition
A1	1	0.72	24-G	100	6-R
A1	2	0.48	24-G	100	6-R
A1	3	0.52	24-G	100	6-R
A11	397	0.94	24-G	100	6-R
A11	398	0.84	24-G	100	6-R
A11	399	0.66	24-G	100	6-R
A111	409	0.95	32-F	144	6-R
A111	410	1.16	48-F	144	6-R
A111	411	0.92	32-F	144	6-R
A1111	421	1.16	24-S	144	6-R
A1111	422	1.30	32-F	144	6-R
A1111	423	1.09	32-F	144	6-R
A18	313	1.47	200-S	267	1
A18	314	1.69	32-S	267	4
A18	315	1.76	72-S[6]	267	3
A2	13	0.71	24-F	267	4-R
A2	14	0.53	24-F	267	3-R
A2	15	0.82	48-S[9]	267	2-R
A22	433	0.61	8-F	267	4-R*
A22	434	0.84	48-S[4]	267	2
A22	435	0.64	20-S[20]	267	3-R
A222	445	1.22	24-S[2]	336	1
A222	447	1.28	OK	336	0
A222	448	1.52	24-S	336	1
A2222	457	1.46	8-S[5]	336	2-B
A2222	458	1.63	24-S[21]	336	3-RB
A2222	459	1.63	32-S[12]	336	2-RB
A28	325	1.52	OK	267	0-B
A28	326	0.98	32-S[5]	267	2-R
A28	327	1.76	267-S[5]	267	0

*Mostly annealed or sandpapered area

Table 13 - Salt-Spray Test Results
(Coatings A3 to A3333 and A38.- A4 to A4444 and A48)

Coating System	Panel Number	Total Film Thickness(Mils)	Hours to Initial Corrosion	Total Hours Tested	Final Condition
A3	25	0.59	8-F	100	6-R
A3	26	0.60	24-F	100	6-R
A3	27	0.50	24-G	100	6-R
A33	469	0.84	8-S^{8}	100	4-R
A33	470	0.94	48-S^{2}	100	4-R
A33	471	0.86	24-S^{5}	100	4-R
A333	481	1.31	144-S^{2}	336	5-R
A333	482	1.11	48-S	336	5-R
A333	483	1.11	144-S	336	5-R
A3333	493	1.62	144-F	336	5-R
A3333	494	1.44	144-S^{4}	336	4-R
A3333	495	1.44	144-S	336	2-R
A38	337	1.17	48-F	264	6-R)
A38	338	1.11	32-S	264	6-R) Very
A38	339	1.38	48-F	264	4-R) Light
A4	37	0.66	24-S^{10}	267	2-R
A4	38	0.61	24-S^{6}	267	2-R
A4	39	0.71	48-F	267	2-R
A44	505	1.10	72-S	267	1-R
A44	506	0.98	48-S^{2}	267	2-R
A44	507	0.90	100-S^{3}	267	1
A444	517	0.98	24-S	336	2-R
A444	518	1.15	336-S	336	1
A444	519	1.11	OK	336	0
A4444	529	1.24	8-S^{2}	336	2-R
A4444	530	1.23	OK	336	0
A4444	531	1.41	OK	336	0
A48	349	1.17	24-S^{3}	264	1
A48	350	1.35	OK	264	0
A48	351	1.31	OK	264	0

Table 14 - Salt Spray Test Results
(Coatings A5 to A5555 and A58 - A6 to A6666 and A68)

Coating System	Panel Number	Total Film Thickness (mils)	Hours to Initial Corrosion	Total Hours Tested	Final Condition
A5	49	0.59	8-F	100	5-R
A5	50	0.57	24-F	100	4-R
A5	51	0.58	24-S[6]	100	4
A55	541	0.80	8-S[2]	267	3-R
A55	542	0.82	24-S[6]	267	4-R
A55	543	0.80	24-S[6]	267	3-R
A555	553	1.00	24-S	336	1-B
A555	554	1.11	247-S[2]	336	2-B
A555	555	1.06	24-S[4]	336	2-B
A5555	565	1.24	192-S	336	2-B
A5555	566	0.99	72-S	336	2-B
A5555	567	0.99	144-S	336	1-B
A58	361	0.79	3-S[3]	264	4-R
A58	362	0.86	48-S	264	2-R
A58	363	0.82	24-S[7]	264	2-R
A6	61	0.38	32-S[10]	267	3
A6	62	0.79	24-S[10]	267	4-R
A6	63	0.65	24-S[15]	267	4-R
A66	577	0.90	8-S	267	2-RB
A66	578	0.94	32-S[2]	267	1-B
A66	579	0.65	24-S[2]	267	3-RB
A666	589	1.24	48-S	336	1
A666	590	1.27	144-S	336	1-B
A666	591	1.13	336-S	336	1-B
A6666	601	1.82	8-S	336	1-R Scratches
A6666	602	1.82	OK	336	0
A6666	603	1.55	OK	336	0
A68	373	0.94	32-S[2]	264	2-R
A68	374	0.88	24-F	264	3-R
A68	375	1.08	24-S[8]	264	1-R

Table 15 - Salt Spray Test Results
(Coatings A7 to A7777 and A78 - A8 to A888)

Coating System	Panel Number	Total Film Thickness (mils)	Hours to Initial Corrosion	Total Hours Tested	Final Corrosion
A7	73	0.38	8-G	100	5*
A7	74	0.37	8-G	100	4
A7	75	0.37	8-G	100	4
A77	613	0.65	8-F	267	4-RB
A77	614	0.60	8-F	267	4-RB
A77	615	0.57	24-F	267	4-RB
A777	625	0.93	8-S^{4}	336	2-RB
A777	626	0.93	24-S^{6}	336	2-RB
A777	627	0.91	24-S^{3}	336	2-RB
A7777	643	1.22	8-S	336	2-RB
A7777	644	1.23	24-S^{5}	336	2-R
A7777	645	1.40	144-S	336	1
A78	385	0.60	24-F	264	4-R
A78	386	0.61	24-S^{12}	264	3-R
A78	387	0.62	24-S^{6}	264	3-R
A8	85	0.79	8-F	100	4
A8	86	0.68	8-F	100	5
A8	87	0.80	24-F	100	4
A88	649	0.84	8-F	267	3-RB*
A88	650	0.84	100-S^{3}	267	2-B
A88	651	0.79	24-F	267	4-RB
A888	661	1.31	144-S	336	1*
A888	662	1.19	24-S	336	1*
A888	663	1.30	OK	336	0
A8888	673	1.62	OK	336	0
A8888	674	1.46	OK	336	0
A8888	675	1.77	OK	336	0

*Mostly annealed or sandpapered area

Table 16 - Salt Spray Test Results
(Coatings B1 to B8)

Coating System	Panel Number	Total Film Thickness (mils)	Hours to Initial Corrosion	Total Hours Tested	Final Condition
B1	846	0.74	24-F	336	5-R
B1	847	0.72	24-F	336	5-R
B1	848	0.66	24-F	336	5-R
B2	858	0.70	192-S[20]	336	2
B2	859	0.59	192-F	336	2
B2	860	0.64	192-F	336	2
B3	870	0.58	24-F	336	5-R
B3	871	0.59	24-F	336	5-R
B3	872	0.56	24-F	336	5-R
B4	882	0.80	24-F	336	3-R
B4	883	0.71	24-F	336	3-R
B4	884	0.88	24-F	336	4-R
B5	894	0.91	31-F	336	4-R
B5	895	0.81	48-F	336	4-R
B5	896	0.76	24-F	336	3-R
B6	906	0.75	48-F	336	3-R
B6	907	0.81	72-S[6]	336	2-R
B6	908	0.74	48-S[6]	336	3-R
B7	918	0.73	24-F	336	4-R
B7	919	0.60	24-F	336	4-R
B7	920	0.69	24-F	336	4-R
B8	930	1.20	227-F	336	2
B8	931	1.17	227-S	336	1
B8	932	1.26	227-F	336	2

Table 17 - Salt Spray Test Results
(Coatings C1 to C8)

Coating System	Panel Number	Total Film Thickness (mils)	Hours to Initial Corrosion	Total Hours Tested	Final Condition
C1	97	0.38	3-S	48	6-R
C1	98	0.32	8-G	48	6-R
C1	99	0.38	8-G	48	6-R
C2	109	0.36	3-S[2]	100	5-R
C2	110	0.41	3-F	100	4-R
C2	111	0.45	8-F	100	3-R
C3	121	0.30	3-G	32	5-R
C3	122	0.25	3-G	32	6-R
C3	123	0.19	3-G	32	6-R
C4	133	0.44	8-F	97	6-R
C4	134	0.35	3-F	32	6
C4	135	0.32	3-F	32	6

Coating System	Panel Number	Total Film Thickness (mils)	Hours to Initial Corrosion	Total Hours Tested	Final Condition
C5	145	0.46	8-F	48	5
C5	146	0.42	3-F	48	6-R
C5	147	0.53	8-F	48	5
C6	157	0.41	3-S	227	5-R
C6	158	0.40	8-F	227	5-R
C6	159	0.46	24-S[20]	227	3-R
C7	169	0.49	3-F	48	4
C7	170	0.36	8-F	48	5
C7	171	0.38	8-F	48	4
C8	181	0.52	8-F	227	6-R
C8	182	0.72	8-S[12]	227	4-R
C8	183	0.71	3-S[3]	227	4-R

Table 18 - Salt Spray Test Results
(Coatings D1 to D8 - D and DD)

Coating System	Panel Number	Total Film Thickness (mils)	Hours to Initial Corrosion	Total Hours Tested	Final Condition
D1	193	0.42	3-F	32	6-R
D1	194	0.33	8-G	32	6-R
D1	195	0.38	8-G	32	6-R
D2	205	0.38	3-F	97	4-R*
D2	206	0.38	24-F	97	4-R
D2	207	0.40	24-F	97	4-R
D3	217	0.30	8-G	32	6-R
D3	218	0.32	3-F	32	6-R
D3	219	0.30	8-F	32	5
D4	229	0.51	8-F	336	4-R*
D4	230	0.60	24-S[8]	336	2-R
D4	231	0.54	8-F	336	4-R
D5	241	0.52	8-F	48	4
D5	242	0.45	8-F	48	4
D5	243	0.46	8-F	48	5
D6	253	0.49	8-S[15]	227	4-R
D6	254	0.44	8-F	227	5-R
D6	255	0.44	8-F	227	5-R
D7	265	0.52	8-S[20]	227	4-R
D7	266	0.47	8-F	227	5-R
D7	267	0.42	8-F	227	5-R
D8	277	0.98	8-S	336	2-B
D8	278	0.82	8-S	336	3-RB
D8	279	0.69	8-S[3]	336	4-RB
DD	289	0.41	3-F	48	4
DD	290	0.36	3-F	48	5
DD	291	.32	8-F	48	5
D	301	.18	3-F	24	6
D	302	.17	3-F	24	6
D	303	.25	8-F	24	4

* Mostly annealed or sandpapered area

Table 19 - Rating of Enamels with Same Primer*

Rank**	Coating System	Film Thickness (mils)	Rank**	Coating System	Film Thickness (mils)
1	A4	0.66	1	C6	0.42
2	A2	0.69	1	C8	0.65
3	A6	0.77	2	C2	0.41
4	A5	0.58	3	C7	0.41
4	A7	0.37	4	C5	0.47
4	A8	0.76	5	C1	0.36
5	A1	0.57	5	C4	0.37
5	A3	0.56	6	C3	0.25
1	B8	1.21	1	D4	0.55
2	B2	0.64	1	D8	0.83
3	B6	0.77	2	D6	0.46
4	B4	0.80	2	D7	0.47
4	B5	0.83	3	D2	0.39
5	B7	0.67	4	D5	0.48
6	B1	0.71	5	D3	0.31
6	B3	0.58	6	D1	0.38

* Do not compare systems with different primers.

** Systems with the lowest rank numbers provide the best protection, systems with same rank provide equal protection.

Table 20 - Rating of Coating Systems Containing Same Enamel*

Gray			White			Red			Black		
** Rank	Coating System	Film Thickness (mils)	** Rank	Coating System	Film Thickness (mils)	** Rank	Coating System	Film Thickness (mils)	** Rank	Coating System	Film Thickness (mils)
1	A18	1.64	1	A28	1.42	1	A3333	1.50	1	A4444	1.29
2	A1111	1.18	1	A222	1.34	2	A333	1.18	1	A48	1.28
3	A111	1.01	2	A2222	1.57	3	A38	1.22	2	A444	1.08
4	A11	0.81	3	A22	0.70	4	A33	0.88	3	A44	0.99
5	A1	0.57	4	A2	0.69	5	A3	0.56	4	A4	0.66
6	C1	0.36	5	C2	0.41	6	D3	0.31	5	D4	0.55
6	D1	0.38	5	D2	0.39	7	C3	0.25	6	C4	0.37

Blue			Yellow			Green			Clear Finish		
** Rank	Coating System	Film Thickness (mils)	** Rank	Coating System	Film Thickness (mils)	** Rank	Coating System	Film Thickness (mils)	** Rank	Coating System	Film Thickness (mils)
1	A5555	1.07	1	A6666	1.73	1	A7777	1.28	1	A8888	1.62
1	A555	1.05	2	A666	1.21	2	A777	0.92	2	A888	1.27
2	A55	0.81	3	A66	0.83	3	A78	0.61	3	A88	0.82
3	A58	0.82	3	A68	0.97	4	A77	0.61	4	D8	0.83
4	A5	0.58	4	A6	0.77	5	A7	0.37	5	C8	0.65
5	D5	0.48	5	C6	0.42	5	C7	0.41	6	A8	0.76
6	C5	0.47	6	D6	0.46	6	D7	0.47			

* Do not compare systems with different enamels.

** Systems with lowest rank number provide the best protection, systems with same rank provide equal protection.

Table 21 - Rating of Enamels

** Rank	Enamel	Average Film Thickness* (mils)
1	Black	0.89
2	Clear	0.99
3	White	0.93
4	Blue	0.75
4	Yellow	0.91
4	Green	0.67
5	Red	0.84
6	Gray	0.85

* Average film thickness of all the systems containing the respective enamels except those with aluminum primer.

** Systems with lowest rank number provide the best protection, systems with same rank provide equal protection.

Accelerated Corrosion High Humidity. The results of the humidity tests are tabulated in tables 22 through 28, which are similar to tables 7 through 18 in which the salt-spray test results are given. The coating systems on these panels were also evaluated using the same rating systems and methods of observation.

The corrosion resulting from high humidity exposure was much less severe than that from salt fog exposure, which is a more corrosive environment. While the final condition rating may indicate the same degree of corrosion, the humidity test panels had much smaller spots of corrosion, although the same number of spots. Note in tables 22 through 28 that none of the panels had runs of corrosion products. Only three coating systems were removed before the full 336 hour exposure period due to excessive corrosion, and these three systems had relatively thin films. The corrosion usually appeared early # -- # during the first 48 hours #-- but did not increase extensively after its initial appearance. In some cases, what had been noted as corrosion spots during the exposure period, could not be located at the final condition evaluation, even with microscopic examination. These disappearing spots may have been extremely small areas of corrosion which later sealed themselves, corrosion from the edges which later washed away, or foreign matter which gave the appearance of corrosion. In any case, the final condition evaluation must be accepted as valid.

No blisters were found between the TFE-resin layers indicating that each of the enamels have good adhesion to each of the primers, that each enamel has good adhesion to itself, and that the Clear Finish has good adhesion to each of the enamels.

For a better picture of the resistance to high-humidity exposure the systems were rated from best to worst. In table 29 the enamels on the same primers are ranked; enamels on different primers should not be compared. Enamels with the same rank number on the same primer provide effectively equal protection. The thickness value is the average film thickness for the three panels of each coating system which were humidity tested. From this table it can be seen that the black, white, and yellow enamels provide the best protection; the gray, red, and blue enamels provide the least protection; and the green enamel and Clear Finish provide protection somewhere in between.

In table 30 the systems containing the same enamel are ranked as to the corrosion protection they provide. Systems containing different enamels should not be compared. Here it can be seen that increasing the film thickness does not necessarily provide more corrosion resistance in a high humidity environment. It points out the advantage of subjecting the panels with three and four coats of the enamels to this test. Also, no consistent difference can be seen in the protection provided by primers A, C, and D. The systems containing the aluminum primer were not included in this table since the aluminum substrate corrodes so differently from the steel that no direct comparison should be made.

Table 31 ranks the enamels based on all the coating systems subjected to the humidity test. The thickness value is the average of all the systems containing the respective enamels except those on the aluminum panels.

As with the salt-spray test results, the black enamel is again rated best, the white enamel third best, and the gray enamel the poorest. The only significant changes in the rankings is that the Clear Finish now is equal to the gray enamel and that the yellow enamel is next to the black.

Additional microscopic examination revealed that very light corrosion, in the form of stains or slightly raised small areas, existed beneath the coatings which had shown very little corrosion. The panels with extensive visible corrosion did not have this corrosion beneath the film, nor did any of the panels subjected to the salt-spray test. The corrosion spotting appeared to be general over the entire panel, although in some instances, raised spots of corrosion were found beneath the larger nodules of TFE-resin. Since the TFE-resin films had to be removed in order to see this corrosion, it was not considered in the final condition evaluation. The detrimental effects of this type of corrosion are not known. Although decreased adhesion may result, it was not indicated by the Shore Durometer or the Bend tests. It is thought that the dry lubricating and wearing properties will be adversely affected.

For the three-and four-coat systems which were not included in tables 30 or 31, more important than rating the enamels is what happened below the coating or on the substrate. During the humidity testing of the three-and four-coat enamel systems very little, if any, corrosion or heavy rust spots were seen; but in the final examination of the substrate for the systems, heavy corrosion which had not penetrated the enamel coating was found. In some cases, mounds of corrosion products were found below the coating. Where the mounds were large, pitting of the substrate occurred. To rate the enamels according to substrate protection, they are the yellow and black enamels which showed little or no rust stain on the substrate. The blue, gray, green, and red enamels showed rust spots, mounds, or the beginning of a formation of corrosion products. The white enamel and Clear Finish gave the poorest protection to the substrate. Numerous mounds of corrosion products formed on the substrate.

Wettability. In all cases, the contract angles for water, methylene iodide, and n-hexadecane on the various TFE-resin primers, enamels, and Clear Finish exceeded the minimum acceptable contact angles. Table 32 lists these contact angles. For any particular determination of the contact angle, that value, if not a reasonably accurate measurement, is lower than the real value for the contact angle given in table 32.

No conclusions could be made concerning the effects of surface roughness in the determination of these contact angles or the effects of the various inorganic pigments.

However, wettability measurements do show that after sintering the various TFE-resin with their various additives, the outer surface of the sintered coating is predominately a TFE-resin surface.

Table 22 - Humidity Test Results (Coatings A1 to 1111 and A18 - A2 to A2222 and A28)

Coating System	Panel Number	Total Film Thickness (mils)	Hours to Initial Corrosion	Total Hours Tested	Final Condition
A1	4	0.43	24-F	336	4
A1	5	0.66	48-S	336	2
A1	6	0.53	24-F	336	1
A11	400	0.73	24-F	336	5)Very
A11	401	0.75	3-S	336	5)Light
A11	402	0.60	3-S	336	4)
A111	412	1.03	OK	336	1
A111	413	0.87	OK	336	1
A111	414	0.98	OK	336	1
A1111	424	1.26	72-S[1]	336	1
A1111	425	1.16	48-S[1]	336	1
A1111	426	1.13	OK	336	0
A18	316	1.43	24-G	336	5)
A18	317	1.47	24-G	336	5)Very
A18	318	1.47	24-G	336	5)Light
A2	16	0.56	72-F	336	2
A2	17	0.64	OK	336	0
A2	18	0.78	48-S[10]	336	2
A22	436	0.67	72-S[4]	336	2
A22	437	0.70	193-S	336	1*
A22	438	0.76	193-S	336	1*
A222	449	1.20	24-S[1]	336	5
A222	450	1.24	192-F	336	5
A222	451	1.15	8-S[2]	336	5
A2222	460	1.57	32-S[3]	336	5
A2222	461	1.56	32-S[1]	336	5
A2222	462	1.52	8-S[2]	336	5
A28	329	1.14	OK	336	0*
A28	330	1.63	32-S[10]	336	3*
A28	331	1.31	72-S[3]	336	2*

* Also contains many very small blisters which are filled with rust and are not detectable with the unaided eye.

Table 23 - Humidity Test Results (Coatings A3 to A3333 and A38 - A4 to A4444 and A48)

Coating System	Panel Number	Total Film Thickness (mils)	Hours to Initial Corrosion	Total Hours Tested	Final Condition
A3	28	0.50	24-G	336	5
A3	29	0.42	24-G	336	4
A3	30	0.53	24-F	336	4
A33	472	0.89	72-F	336	2
A33	473	0.89	48-F	336	2
A33	474	0.86	24-S	336	1
A333	484	1.11	96-S[2]	336	1
A333	485	1.20	96-S[1]	336	1
A333	486	1.22	48-S	336	2
A3333	496	1.51	192-S[1]	336	1
A3333	497	1.41	OK	336	0
A3333	498	1.13	72-S[5]	336	1
A38	340	1.08	OK?	336	1
A38	341	1.31	48-S[3]	336	1
A38	342	1.17	24-S	336	1
A4	40	0.57	48-S	336	0
A4	41	0.69	OK	336	0
A4	42	0.66	48-S[5]	336	1
A44	508	0.98	48-S[5]	336	0
A44	509	0.96	3-S[2]	336	0
A44	510	0.91	265-S[3]	336	0
A444	520	0.98	32-S[1]	336	0
A444	521	1.16	OK	336	0
A444	522	1.30	OK	336	0
A4444	532	1.46	OK	336	0
A4444	533	1.44	OK	336	0
A4444	534	1.44	OK	336	0
A48	352	1.11	24-F	336	1
A48	353	1.11	OK	336	0
A48	354	0.99	OK	336	0

Table 24 - Humidity Test Results (Coatings A5 to A5555 and A58 - A6 to A6666 and A68)

Coating System	Panel Number	Total Film Thickness (mils)	Hours to Initial Corrosion	Total Hours Tested	Final Condition
A5	52	0.52	24-G	336	5) Very
A5	53	0.64	72-S[5]	336	5) Very
A5	54	0.66	24-G	336	5) Light
A55	544	0.80	48-S	336	4) Very
A55	545	0.72	48-S	336	4) Light
A55	546	0.74	48-F	336	4)
A555	556	0.98	OK	336	0
A555	557	1.31	OK	336	0
A555	558	1.03	32-S[2]	336	1
A5555	568	1.20	72-S[2]	336	1
A5555	569	1.11	192-S[1]	336	1
A5555	570	1.12	OK	336	1
A58	364	0.82	8-S	336	4) Very
A58	365	0.94	98-S	336	4) Light
A58	366	0.81	72-F	336	4)
A6	64	0.49	100-S	336	1
A6	65	0.84	24-S	336	1
A6	66	0.96	32-S[3]	336	0
A66	580	0.79	----	336	1
A66	581	0.80	OK	336	0
A66	582	0.87	243-S	336	1
A666	592	1.13	OK	336	0
A666	593	1.27	OK	336	0
A666	594	1.13	OK	336	0
A6666	604	1.62	OK	336	0
A6666	605	1.69	OK	336	0
A6666	606	1.63	OK	336	0
A68	376	1.08	OK?	336	1
A68	377	1.11	OK?	336	1
A68	378	0.86	OK?	336	2

Table 25 - Humidity Test Results (Coatings A7 to A777 and A78 - A8 to A8888)

Coating System	Panel Number	Total Film Thickness(mils)	Hours to Initial Corrosion	Total Hours Tested	Final Condition
A7	76	0.28	3-S[3]	336	4
A7	77	0.36	3-F	336	3
A7	78	0.41	3-S	336	2
A77	616	0.58	24-S[5]	336	1
A77	617	0.60	32-S	336	1
A77	618	0.56	24-S	336	1
A777	628	1.13	72-S	336	1
A777	629	0.94	OK	336	0
A777	630	1.00	OK	336	0
A7777	640	1.31	OK	336	0
A7777	641	1.18	OK	336	1
A7777	642	1.41	OK	336	0
A78	388	0.69	OK	336	1
A78	389	0.69	97-S	336	2
A78	390	0.66	265-S[3]	336	2
A8	88	0.66	8-F	336	3
A8	89	0.68	3-S[2]	336	3
A8	90	0.86	32-F	336	2
A88	652	0.79	24-S[6]	336	2
A88	653	0.84	8-F	336	4
A88	654	0.77	24-F	336	5
A888	664	1.20	32-S	336	5
A888	665	1.27	48-S	336	5
A888	666	1.30	OK	336	5
A8888	676	1.57	72-S	336	5
A8888	677	1.66	32-G	336	5
A8888	678	1.56	48-S	336	5

Table 26 - Humidity Test Results
(Coatings B1 to B8)

Coating System	Panel Number	Total Film Thickness (mils)	Hours to Initial Corrosion	Total Hours Tested	Final Condition
B1	849	0.66	OK	336	0
B1	850	0.75	OK	336	0
B1	851	0.58	OK	336	0
B2	861	0.77	OK	336	0
B2	862	0.71	OK	336	0
B2	863	0.78	OK	336	0
B3	873	0.63	48-F	336	0
B3	874	0.62	48-S^{4}	336	0
B3	875	0.68	OK	336	0
B4	885	0.76	48-S^{4}	336	1
B4	886	0.91	48-S^{10}	336	2
B4	887	0.88	48-S^{10}	336	2
B5	897	0.88	336-S	336	0
B5	898	0.92	72-S	336	0
B5	899	0.84	24-S^{2}	336	1
B6	909	0.70	OK	336	0
B6	910	0.62	OK	336	0
B6	911	0.68	OK	336	0
B7	921	0.63	OK	336	0B
B7	922	0.75	OK	336	0B
B7	923	0.84	OK	336	0B
B8	933	1.27	OK	336	0
B8	934	1.10	OK	336	0
B8	935	1.18	OK	336	0

Table 27 - Humidity Test Results
(Coatings C1 to C8)

Coating System	Panel Number	Total Film Thickness (mils)	Hours to Initial Corrosion	Total Hours Tested	Final Condition
C1	100	0.42	3-S	336	5
C1	101	0.40	8-G	336	5
C1	102	0.32	8-G	336	5
C2	112	0.39	8-S	336	2
C2	113	0.38	24-S^{5}	336	1
C2	114	0.42	24-S^{2}	336	1
C3	124	0.23	3-G	32	6
C3	125	0.21	3-G	32	6
C3	126	0.26	3-G	32	5
C4	136	0.49	8-S^{3}	336	2
C4	137	0.35	3-F	336	3
C4	138	0.38	3-F	336	4
C5	148	0.41	3-F	336	4) Very
C5	149	0.42	3-S^{2}	336	4) Light
C5	150	0.47	3-F	336	4)
C6	160	0.41	24-S^{6}	336	2
C6	161	0.41	24-S^{3}	336	1
C6	162	0.45	8-S	336	2
C7	172	0.41	24-F	336	4
C7	173	0.39	3-F	336	4
C7	174	0.37	8-S	336	4
C8	184	0.87	3-S	336	3
C8	185	0.71	8-S	336	3
C8	186	0.66	8-S^{2}	336	3

Table 28 - Humidity Test Results
(Coatings D1 to D8-D and DD)

Coating System	Panel Number	Total Film Thickness (mils)	Hours to Initial Corrosion	Total Hours Tested	Final Condition
D1	196	0.42	3-F	97	5
D1	197	0.46	8-F	97	6
D1	198	0.36	3-F	97	6
D2	208	0.40	8-F	336	3
D2	209	0.42	8-S5	336	3
D2	210	0.35	24-F	336	3
D3	220	0.29	3-G	32	6
D3	221	0.33	3-G	32	5
D3	222	0.41	3-G	32	5
D4	232	0.60	32-S	336	1
D4	233	0.62	24-S10	336	1
D4	234	0.58	32-F	336	1
D5	244	0.36	3-F	336	5)
D5	245	0.41	3-F	336	5) Light
D5	246	0.34	3-F	336	5)
D6	256	0.34	24-S2	336	2
D6	257	0.44	8-S	336	2
D6	258	0.36	48-S6	336	2
D7	268	0.48	24-S8	336	3
D7	269	0.49	24-S10	336	2
D7	270	0.47	24-S4	336	2
D8	280	0.82	24-S	336	1
D8	281	0.66	24-S	336	1
D8	282	0.72	32-S	336	1
DD	292	0.36	32-S1	336	1
DD	293	0.38	32-S2	336	1
DD	294	0.35	32-S1	336	1
D	304	0.17	24-S12	336	2
D	305	0.18	24-S7	336	2
D	306	0.15	24-S15	336	2

Table 29 - Rating of Enamels with Same Primer*

Rank**	Coating System	Film Thickness (mils)	Rank**	Coating System	Film Thickness (mils)
1	A4	0.64	1	C2	0.40
2	A6	0.76	2	C6	0.42
3	A2	0.66	3	C8	0.75
4	A1	0.54	4	C4	0.41
5	A8	0.73	5	C7	0.39
6	A7	0.35	6	C5	0.43
7	A3	0.48	7	C1	0.38
8	A5	0.61	8	C3	0.23
1	B1	0.66	1	D8	0.73
1	B2	0.75	1	D4	0.60
1	B3	0.64	2	D6	0.38
1	B6	0.67	2	D7	0.48
1	B8	1.18	3	D2	0.39
2	B7	0.75	4	D5	0.37
3	B5	0.88	5	D3	0.34
4	B4	0.85	6	D1	0.41

* Systems with different primer should not be compared.

** Systems with lowest rank number provide the best protection, systems ranked the same provide equal protection.

Table 30 - Rating of Coating Systems Containing Same Enamel *,***

Gray			White			Red			Black		
** Rank	Coating System	Film Thickness (mils)	** Rank	Coating System	Film Thickness (mils)	** Rank	Coating System	Film Thickness (mils)	** Rank	Coating System	Film Thickness (mils)
1	A1	0.54	1	A22	0.71	1	A38	1.19	1	A44	0.95
2	A11	0.69	2	A28	1.36	2	A33	0.88	1	A48	1.07
2	A18	1.46	3	A2	0.66	3	A3	0.48	2	A4	0.64
3	D1	0.41	4	C2	0.40	4	D3	0.34	3	D4	0.60
3	C1	0.38	5	D2	0.39	5	C3	0.23	4	C4	0.41

Blue			Yellow			Green			Clear		
** Rank	Coating System	Film Thickness (mils)	** Rank	Coating System	Film Thickness (mils)	** Rank	Coating System	Film Thickness (mils)	** Rank	Coating System	Film Thickness (mils)
1	A55	0.75	1	A6	0.76	1	A77	0.58	1	A8	0.73
1	A58	0.86	1	A66	0.82	1	A78	0.68	2	A88	0.80
2	C5	0.43	2	A68	1.02	2	D7	0.48	2	C8	0.75
3	A5	0.61	3	C6	0.42	3	A7	0.35	1	D8	0.73
4	D5	0.37	4	D6	0.38	4	C7	0.39			

* Do not compare systems with different enamels.

** Systems with lowest rank number provide the best protection, systems with the same rank number provide equal protection.

*** Three-and four-coat enamel systems are not included.

Table 31 - Rating of Enamels

Rank**	Enamel	Average Film Thickness (mils)
1	Black	0.73
2	Yellow	0.68
3	White	0.70
4	Green	0.50
5	Red	0.62
6	Blue	0.60
6	Gray	0.78
6	Clear	0.76

* Enamels of the three and four coat systems are not included.

** Enamels ranked lowest (lowest number) provide the best protection, enamels with the same rank number provide equal protection.

*** Average film thickness of all the coating systems containing the respective enamel except from those with aluminum primer.

Table 32 - Wettability Measurements on TFE-resin Coated Panels

Coating System	Panel No.	Coating Thickness	Surface Roughness*	Contact of Angles (in degrees) Water	Methylene Iodide	n-Hexadecane
A1	7	0.59	79	113	89	44
A1	8	0.53	71	107	89	40
A11	403	0.73	70	113	85	42
A11	404	0.72	80	116	88	45
A111	415	0.92	75	111	85	45
A111	416	0.92	76	113	88	45
A1111	427	1.37	95	128	91	50
A1111	428	1.37	86	108	89	40
A2	18	0.78	68	134	91	51
A2	20	0.59	85	122	92	41
A22	439	0.84	73	112	88	39
A22	440	0.71	64	112	86	41
A222	452	1.28	71	125	91	45
A222	453	1.27	72	116	91	47
A2222	463	1.52	78	129	96	50
A2222	464	1.57	55	109	88	43
A3	31	0.53	61	111	91	37
A3	33	0.61	90	115	90	49
A33	475	0.99	96	110	86	40
A33	476	0.89	89	107	84	47
A333	487	1.30	98	116	84	46
A333	488	1.32	90	114	84	47
A3333	499	1.56	120	106	84	42
A3333	500	1.46	132	108	85	45
A4	43	0.61	64	121	82	56
A4	44	0.66	58	113	88	47
A44	511	1.00	78	124	85	49
A44	512	0.96	75	112	82	51
A444	523	1.22	91	124	85	49
A444	524	1.12	102	125	84	51
A4444	535	1.35	105	125	89	58
A4444	536	1.28	109	115	87	52

*Average Microinches where contact angle was measured.

Table 32 - Wettability Measurements on TFE-resin Coated Panels (Continued)

Coating System	Panel No.	Coating Thickness (mils)	Surface Roughness *	Contact of Angles (in degrees)		
				Water	Methylene Iodide	n-Hexadecane
A5	55	0.61	82	133	88	54
A5	56	0.65	68	123	89	52
A55	547	0.86	68	119	85	45
A55	548	0.86	62	109	86	49
A555	559	1.07	83	122	95	58
A555	560	1.00	80	121	87	51
A5555	571	1.26	81	119	92	59
A5555	572	1.01	84	113	85	49
A6	67	1.31	170	151	97	62
A6	69	0.80	118	140	99	55
A66	584	1.17	75	109	88	51
A66	585	1.03	70	121	91	49
A666	595	1.22	73	114	86	52
A666	596	1.39	61	129	91	49
A6666	607	1.66	130	134	105	55
A6666	608	1.63	85	118	86	40
A7	79	0.40	49	118	90	50
A7	80	0.35	52	116	89	56
A77	619	0.61	79	123	87	47
A77	620	0.49	74	122	87	50
A777	631	0.98	75	122	85	46
A777	632	1.00	76	121	81	48
A7777	637	1.44	96	142	102	59
A7777	638	1.46	90	117	85	50
A8	91	0.79	66	140	96	50
A8	94	0.80	60	121	89	52
A88	656	0.82	63	113	84	45
A88	658	0.84	59	114	83	44
A888	667	1.24	85	112	85	45
A888	668	1.24	90	117	82	49
A8888	679	1.74	91	138	84	55
A8888	680	1.37	95	119	90	48
A	841	0.15	18	128	89	48
B	966	0.30	28	121	90	40
C	843	0.12	39	133	90	47
D	307	0.14	35	124	95	49
DD	295	0.35	53	116	89	53

CONCLUSIONS

The results of the various quality tests of the 68 TFE-resin coating systems led to the following conclusions:

Microscopic examination is a definite aid in determining the quality of TFE-resin coatings. Thirty X magnification will reveal all the defects of the film, aside from those which are inherent, and will supplement many of the other quality tests.

Pinholes visible at 30X magnification should not be cause for rejection if they are not to the substrate.

Mudcracks visible at 30X magnification in one-coat enamel films used as a topcoat should not be cause for rejection if they are not to the substrate.

Film thickness cannot be adequately controlled by visual means alone, and some instrument such as a Magne Gage for ferrous substrates, or a Filmmeter or Dermitron for non-ferrous substrates should be employed for its measurement.

TFE-resin films have an inherent surface roughness which is somewhat dependent on the total film thickness. The surface roughness, however, can be controlled and 90 average microinches is a reasonable maximum limit. Where TFE-resin films are to have antisticking application, a lower surface roughness would be advisable, but the exact value would depend on the specific application.

A Brush Surfindicator is an adequate, nondestructive instrument for determining the surface roughness of TFE-resin films.

The Bend Test is a more reliable method than the Shore Durometer Test for determining the adhesion of TFE-resin films to a substrate. It is, however, a destructive test, requiring specially prepared specimens while the Shore Durometer Test can be performed on most flat surfaces and is nondestructive.

The four TFE-resin primers provide adequate adhesion to the substrate regardless of the coating system used.

TFE-resin coating systems with a total fused film thickness of less than 0.9 mil do not provide dependable salt-spray protection for any length of time.

TFE-resin coating systems with a fused film thickness in excess of 0.9 mil (except systems containing gray enamel) provide adequate protection (less than one spot of corrosion per square inch area and no runs) when subjected to 32 hours salt-spray exposure.

For optimum corrosion protection (salt spray and high humidity) black enamel TFE-resin coating should be used. In humid environment, the black and yellow enamels give the best protection. For the coating system with good corrosion protection and for use as a thin lubricating coating, refer to tables 19 and 30 to select the system, then to tables 21 and 31 for the ranking of the enamels.

A 16-hour, 20 percent salt-spray test is a good continuity test; its main drawback is that it is destructive.

The value of a high humidity test for determining the corrosion protection provided by the TFE-resin coating is informative. From the different degrees of corrosion of the substrate by various TFE-resin enamel coatings, they can be easily rated. This test, however, for determining the adhesion of the individual coating to each is not known because no blisters were formed between any of the coatings investigated.

Contact angles as determined by the wettability tests are desirable in that a predominately TFE-resin surface is shown. Such tests performed on material as ordered may possibly reveal the minimum amount of TFE-resin, by weight, in a dispersion that would be necessary for coating applications. Wettability tests also may reveal a contaminated TFE-resin surface due to faulty coating procedures.

PART 2

APPLICATION OF TFE-RESIN FILMS ON ALUMINUM ALLOYS

INTRODUCTION

The total heat treating time at sintering temperature required to prepare thin films of TFE-resins may have a detrimental effect on the mechanical properties of aluminum alloys, especially those in the hardened condition. It is, therefore, desired to obtain the time required to heat the surface of aluminum alloys of various cross sectional thickness to 700°F, so that a minimum sintering time may be used. It is understood that the variables which affect the rate of heating are numerous; type of furnace, furnace capacity, furnace load, method of heating (using a preheated furnace versus heating furnace from room temperature), the thermal conductivity of the metal, its surface condition, and the presence or absence of thermal insulating coatings on the metal. It was decided to select the set of conditions which would result in data to establish a table similar to that in section 3.3.1 of "Proposed Revision of NAVWEPS OD 10362" which is appendix A of NAVWEPS Report 6948.[2]

Section A of part 2 encompasses the investigation of the rate of heating of the surfaces of aluminum alloys to sintering temperature. In addition, it was desired to find the effect of heat-treating cycles encountered in TFE-resin sintering on the mechanical properties of a number of specific aluminum alloys in their various hardness conditions. A study of the effects of heat treatment of specific aluminum alloys is presented in section B of part 2.

SECTION A - RATE OF HEATING OF ALUMINUM ALLOYS

EXPERIMENTAL PROCEDURE

To determine the time required to heat the surface of aluminum alloy specimens of various cross sectional thicknesses to a temperature sufficient to sinter thin coatings of TFE-resins, alloys 3003-F and 5086-F were selected because they have thermal conductivities which approach the extremes for aluminum alloys (3003 is 0.46 cgs units at 25°F and 5086 is 0.30 cgs units at 25°F).

> Note: Cgs units = calories per square centimeter per centimeter of thickness per degree centigrade.

Specimen blocks, 4-inches by 4-inches by $\frac{1}{4}$-inch, $\frac{1}{2}$-inch, 1-inch, $1\frac{1}{2}$-inches, and 2-inches were prepared from the two alloys, and, after having been heated in air at 700°F for 30 minutes to oxidize the surface, were placed in a room temperature furnace. Thermocouples were inserted in holes which had been drilled parallel to the 4-inch by 4-inch surface and within 1/16 inch of it. (Attempts had been made to attach the thermocouples to the surface, but none were successful. Although the thermocouples will not exactly indicate the surface temperature, it is thought they will indicate a value within a few degrees of that at the surface.) After placing the thermocouples in good contact with the aluminum, the holes were plugged with asbestos and the furnace heated to 700° ± 3°F. When the furnace reached 700°F the temperature of the blocks was recorded at 4-minute intervals until 690°F (in some cases, 700°F) was attained.

The same blocks were completely coated with TFE-resin aluminum primer by spraying, were air dried for 24 hours at room temperature, and tested as previously described. The same blocks were then coated with TFE-resin gray enamel (this was considered the second coat), and after air drying a minimum of 24 hours the same test procedure was repeated. A second coat of gray enamel was applied (this was considered the third coat) and again tested.

A different set of identical blocks were subjected to identical tests except that the temperature of the furnace was raised to and maintained at 750°F, a temperature sometimes used for sintering TFE-resin films. Again, the temperature indicated by the thermocouples was recorded at 4-minute intervals until 740°F (in some cases, 750°F) was attained.

RESULTS AND DISCUSSION

The time required for the surfaces of block specimens of two aluminum alloys with increasing cross sectional thickness to reach the furnace temperature after the furnace has attained the desired temperature is recorded in table 33. The first number in each column is the time in minutes required for the blocks to reach 10°F below the indicated temperature; the second number in each column is the time required for the blocks to attain the indicated temperature.

From table 33 it is evident that thicker blocks require longer heating times than thinner blocks, and that no significant difference exists in the rate of heating between the two alloys, especially with the thicker specimens.

Comparison of the heating time for the different conditions should not be taken at face value, because the time required to heat the furnace to the specified temperature varied in some cases. Where available it is recorded in table 34. It should be noted, however, that this variable has a greater influence on the rate of surface heating than the presence or absence of the thin thermoinsulating TFE-resin film.

Figures 2 and 3 are typical of those from which the data for table 33 was obtained. It can be seen that as the surface temperature of the blocks approaches that of the furnace, the rate of heating is decreased. This is much more pronounced with the thicker blocks and with the coated blocks, so much so, that 2 hours after the furnace had reached the specified temperature some of the blocks had not. For this reason the test was discontinued in most instances when the temperature of the block reached 10°F below the furnace temperature.

After the TFE-resin coated blocks had been subjected to these heat treatments they were examined, and the films were found to be completely cured.

It is realized that this experimental work could have been performed with better control of the variables, such as the rate of heating the furnace and furnace temperature at the specified temperatures. This would have produced a table with too many qualifying factors for other than laboratory work. It is believed that the data obtained results in more useful information than if the variables had been more closely controlled.

With the other conditions being the same, the following observations were made:

1. Pieces of thick cross section require longer to attain a specified temperature than pieces of thin cross section.

Table 33 - Time Required for Aluminum Specimens to Attain Furnace Temperature after Furnace has Reached Desired Temperature (in minutes)

3003 Aluminum

Specimen Thickness (in)	700°F				750°F			
	Uncoated	Primer Coat	Second Coat	Third Coat	Uncoated	Primer Coat	Second Coat	Third Coat
1/4	9-21*	16-	9-	9-	7-19	11-	10-	13-
1/2	14-26	19-	12-	20-	17-28	22-	20-	20-
1	31-71	36-	40-	36-	30-60	34-	29-	29-
1 1/2	34-71	40-	42-	51-	33-60	36-	39-	32-
2	52-	42-	48-	36-	51-	45-	39-	34-

5086 Aluminum

Specimen Thickness (in)	700°F Uncoated	700°F Primer Coat	700°F Second Coat	700°F Third Coat	750°F Uncoated	750°F Primer Coat	750°F Second Coat	750°F Third Coat
1/4	0-9	9-	6-	20-	5-9	12-	13-	22-
1/2	8-20	14-	10-	20-	9-15	20-	19-	23-
1	22-54	33-	41-	54-	21-50	26-	42-	29-
1 1/2	26-59	34-	42-	54-	22-50	35-	44-	31-
2	49-	42-	48-	37-	46-	44-	44-	35

* Second number indicates time for specimen to attain temperature indicated. First number gives time for specimens to attain 10° below temperature indicated.

Table 34 - Time Required for Furnace to Attain Indicated Temperature (in minutes)

3003 Aluminum

Specimen Thickness (in)	700°F				750°F			
	Uncoated	First Coat	Second Coat	Third Coat	Uncoated	First Coat	Second Coat	Third Coat
1/4	90	90	---	---	80	---	---	---
1/2	90	90	---	---	80	---	---	---
1	90	100	105	---	95	---	---	---
1 1/2	90	100	105	---	95	---	---	---
2	98	95	---	---*	100	---	105	---

5086 Aluminum

Specimen Thickness (in)	700°F Uncoated	700°F First Coat	700°F Second Coat	700°F Third Coat	750°F Uncoated	750°F First Coat	750°F Second Coat	750°F Third Coat
1/4	90	90	---	---	80	---	---	---
1/2	90	90	---	---	80	---	---	---
1	90	100	105	---	95	---	---	---
1 1/2	90	100	105	---	95	---	---	---
2	98	95	---	---*	100	---	105	---

* Furnace at 708°F

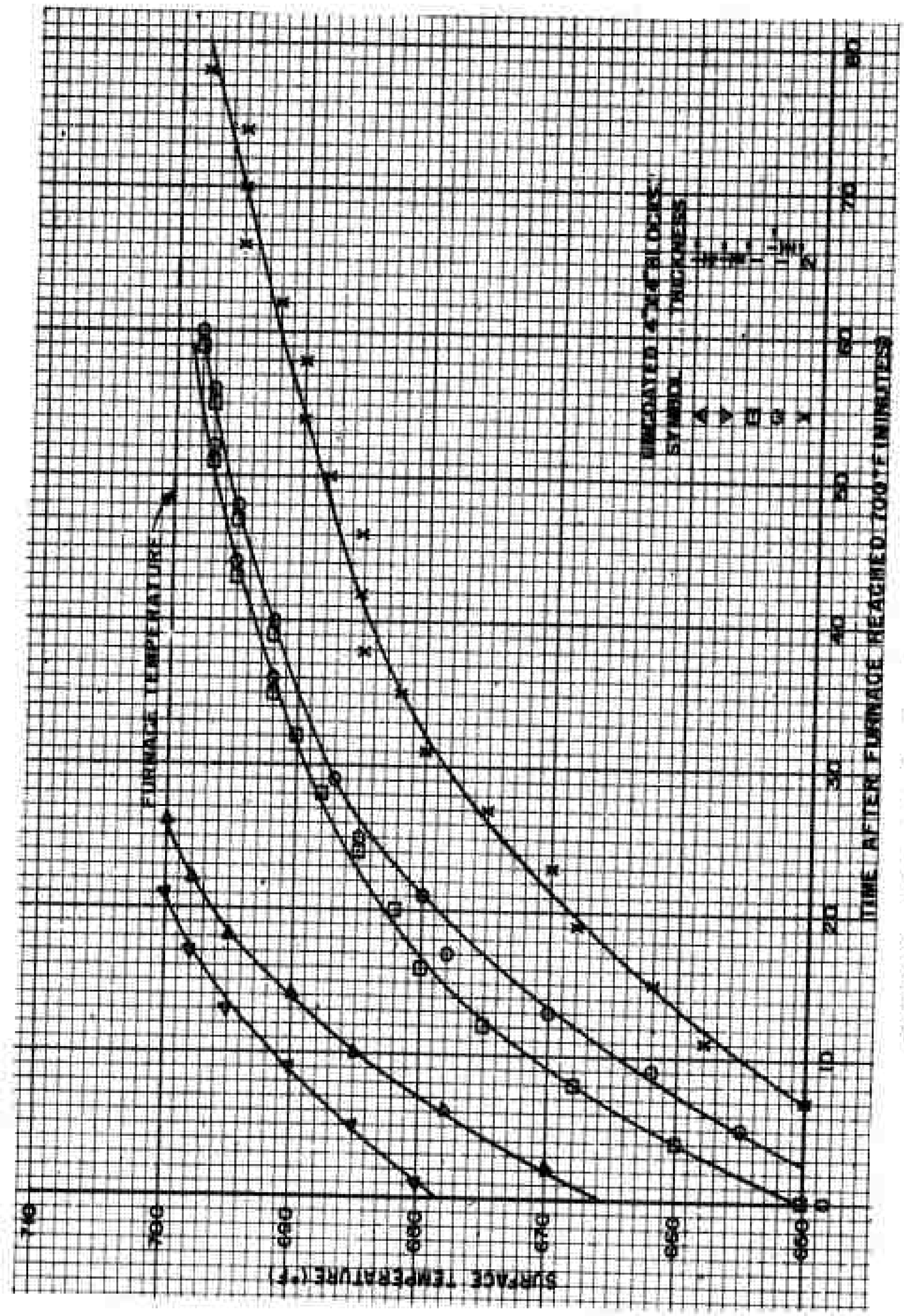

Figure 2 - Change in Surface Temperature with Time - Alloy 5086

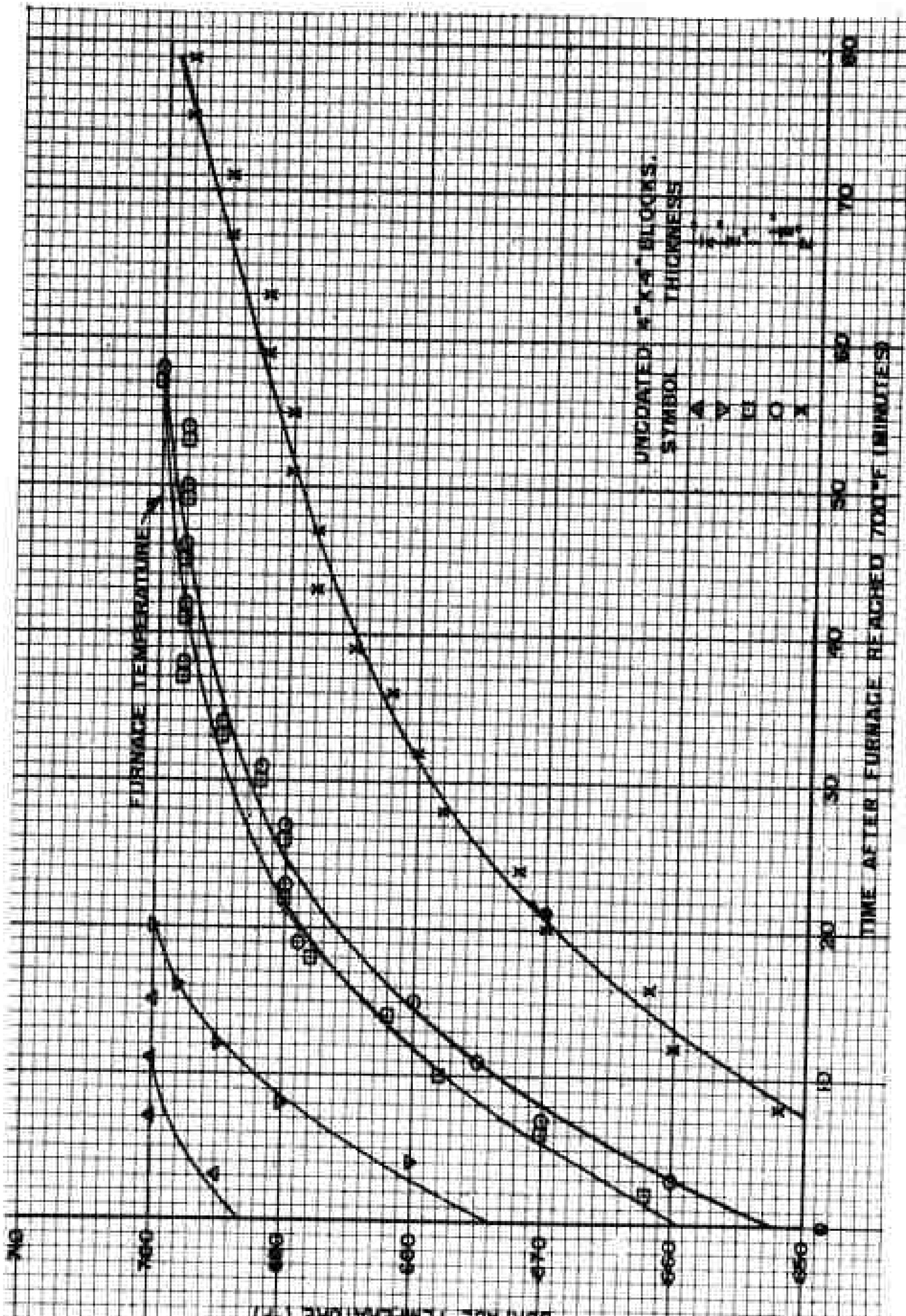

Figure 3 - Change in Surface Temperature with Time - Alloy 3003

2. TFE-resin coated objects require a longer time to attain a specified temperature than same size uncoated objects.

3. The thicker the TFE-resin film, the more time it requires to reach a specific temperature.

4. The rate of heating the furnace (10 minutes difference in a total of 90 minutes) has greater influence than the presence or absence of a TFE-resin coating 0.3 mil thick.

5. Eight degrees variation in furnace temperature will cause a greater change in required time than a variation of 1 inch in the cross section thickness. See footnote table 34.

CONCLUSIONS

A table of the type desired, at best can be only approximate. Too many uncontrollable variables exist for it to be exact.

Only an approximate table is needed for if the mechanical properties of the aluminum alloy substrate are going to be changed, they will be changed upon reaching the sintering temperature and not because they have been subjected to the temperature for a specific time. (See the results of part 2, section B.

Comparison of table 33 with the Fusing Time Table of NAVWEPS OD 10362 (Steel Surfaces) shows the two to be sufficiently alike so that the latter may be used as an approximate Fusing Time Table for aluminum alloys.

Section B - Effects of Heat Treating on Mechanical Properties of Specific Aluminum Alloys

EXPERIMENTAL PROCEDURE

The work performed in this section of the investigation was undertaken to determine the effect of heat treatments, required in the application of thin films of TFE-resins, on the mechanical properties of some hardened aluminum alloys. The following aluminum alloys were investigated:

Alloy	Temper	Alloy	Temper
3003	0	5154	0
3003	0-A	5154	H-32
3003	H-12	5154	H-34
3003	H-14	5154	H-36
3003	H-16	5154	H-38
3003	H-18	5056	0

From 16 gauge sheets (0.0625 inch thick), 12 tensile specimens of each alloy-temper condition were prepared according to Federal Test Method Standard No. 151, Method No. 211, Type F2. The specimens of each condition were divided into four groups and handled as follows before being tested:

1. Group A was tested as received.

2. Group B was heated to 700°F and allowed to aircool to room temperature.

3. Group C was treated as Group B, then heated to 700°F, maintained for 5 minutes at this temperature, and quenched with a water spray.

4. Group D was treated as Group C, then heated, and quenched a second time.

Except for Group A, all specimens were placed in a room-temperature furnace and the temperature raised to 700°F. The furnace used was a large, walk-in, recirculating, hot-air type.

The heat treatments used were to simulate those encountered in the sintering of TFE-resin films. Group A gave the mechanical properties as received; Group B, the properties after an oxidation heat treatment; Group C, the properties after the primer coat had been sintered; and Group D, the properties after an enamel coat had been sintered.

The mechanical properties obtained were tensile strength, yield strength in 0.2 percent offset, elongation in 2.00 inches, and hardness in Rockwell superficial 15-T values.

It was indicated in NAVWEPS Report 6849[3] that no reaction takes place between aluminum alloys and TFE-resin coating during the sintering process which affects the mechanical properties of the alloys; therefore, in this investigation, it was not necessary to coat the aluminum specimens.

RESULTS AND DISCUSSION

The results of the mechanical property tests of the aluminum alloys subjected to TFE-resin sintering heat treatments are summarized in table 35, in which each value is the average for three specimens. The yield strength was not obtained for the 3003 alloys, as the specification covering this alloy does not call for it. The alloy identified as 3003-OA is the same as 3003-O, but from different sheet stock. The first value in the hardness column is in Rockwell 15-T superficial value, the second in Brinell 500 kg. load, 10mm ball value which has been converted from the Rockwell scale where possible.

As expected, the mechanical properties of the annealed alloys were effectively the same before and after the simulated TFE-resin sintering heat treatments. Considering the properties of the hardened 3003 alloys, the first heat treatment (Group B specimens) with the slow cool caused the largest change with the resultant mechanical properties approaching those of the annealed alloy. The second heat treatment (Group C specimens) followed by a water quench tended to reverse slightly the direction of the change. For the third heat treatment (Group D specimens) followed by a water quench, the mechanical properties again approached those of the annealed alloy.

With the hardened 5154 alloys, except 5154-H32, the mechanical properties were also effectively changed to those of the annealed alloy after the first heat treatment and the final mechanical properties showed no significant changes for subsequent heat treatments. The mechanical properties of 5154-H32 fall approximately half way between the annealed and hardened condition after the first and subsequent heat treatments.

Table 35 - Mechanical Properties of Aluminum Alloys

Alloy & Temper	Group	Yield Strength (psi)	Tensile Strength (psi)	Elongation (%)	Hardness	Alloy	Group	Yield Strength (psi)	Tensile Strength (psi)	Elongation (%)	Hardness
3003-0	A	-	17100	34.8	41-	5154-0	A	18900	36400	23.2	73-73
	B	-	17100	35.3	39-		B	18600	36500	24.7	74-75
	C	-	17700	35.0	39-		C	18900	36700	23.7	71-68.5
	D	-	17100	37.0	39-		D	18800	36700	24.8	71-68.5
3003-04	A	-	16300	35.8	41-	5154-H32	A	26800	40000	14.7	76-80
	B	-	16200	34.8	38-		B	24200	38500	17.8	74-75
	C	-	16900	35.7	37-		C	23700	38100	18.0	74-75
	D	-	16500	37.0	37-		D	23000	38100	17.3	73-73
3003-H12	A	-	19700	8.8	54-	5154-H34	A	32600	43800	12.5	79-90
	B	-	17800	19.7	58-		B	17900	37500	20.3	70-66.5
	C	-	18300	20.5	54-		C	18600	37000	20.6	70-66.5
	D	-	18000	23.0	51-		D	18300	38100	20.7	70-66.5
3003-H14	A	-	22800	7.3	63-56	5154-H36	A	36100	46300	11.7	81-99
	B	-	17200	27.5	47-		B	18500	37700	23.0	70-66.5
	C	-	17900	26.0	50-		C	17900	38100	24.3	69-65
	D	-	16000	33.0	40-		D	17300	36500	24.0	69-65
3003-H16	A	-	26000	6.5	67-61	5154-H38	A	43400	51600	11.0	82-104
	B	-	16000	36.7	37-		B	19100	37900	24.3	73-73
	C	-	16500	36.3	37-		C	19100	37700	23.5	69-65
	D	-	15800	37.5	32-		D	19400	37700	22.7	70-66.5
3003-H18	A	-	34700	6.5	76-80	5056-0	A	21900	42100	28.3	74-75
	B	-	17500	34.0	38-		B	21600	41700	29.3	72-71
	C	-	18000	33.0	38-		C	20900	41600	27.5	74-75
	D	-	17200	34.0	40-		D	21600	42700	26.8	71-68.5

The reduction in tensile strength and hardness and the increase in the elongation of the tempered aluminum alloys showed that the "TFE-resin sintering" heating cycle was detrimental. It was the Group B step (oxidizing) that gave the greatest change in mechanical properties.

CONCLUSIONS

Aluminum alloys 3003 and 5154 in their hardened condition will have their mechanical properties changed when they are subjected to temperatures required to sinter thins films of TFE-resins. The change in the properties is effectively to those of the annealed condition. It can be expected that all other hardened aluminum alloys will undergo a similar change in mechanical properties.

RECOMMENDATIONS

1. Tests should be performed to ascertain the maximum temperature for sintering TFE-resin coating. Temperature above 800°F cause the TFE-resin coating to soften and to apparently breakdown. Also, the enamel adhesion to the primer is decreased.

2. A determination should be made to find out the initial harmful corrosion time of ferrous substrate material coated with TFE-resin. Such material exposed to high humidity undergoes corrosion which is not evident by visual observation.

3. An investigation should be undertaken to determine how additives put in aqueous dispersions of TFE-resin can improve application of the dispersion and result in an improved quality of coating.

4. Aluminum alloys in the hardened condition should not be coated with TFE-resin films if their mechanical properties are to be maintained, because coating effectively reduces their mechanical properties to those of the annealed condition.

ACKNOWLEDGEMENTS

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EVALUATION OF AQUEOUS DISPERSIONS OF TFE-FLUOROCARBON RESINS (TEFLON) APPLIED AS THIN FILMS TO METAL SUBSTRATES, by J.H. Thompson and C.L. Scott. 1 August 1961. 66p., incl. illus., table (NWPW-T-1-61)

(UNCLASSIFIED)

TFE-resin "Teflon" coating systems were prepared on steel and aluminum specimens from proprietary TFE-resin primer and enamel coating material. The resultant 68 systems were evaluated using visual and microscopic examination, film thickness, surface roughness, adhesion, accelerated corrosion (salt spray and high humidity), and wettability tests. The results show the four primers to provide good adhesion and equal corrosion protection, the corrosion protection to be dependent on the total film thickness, the black and white enamels to provide superior corrosion protection, and the

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1. Thin films - Test results.
2. Teflon - Test results.
3. Metal substrates - Protective coatings.

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